



**Deutsche Gesellschaft  
für Luft- und Raumfahrt  
Lilienthal-Oberth e.V.**

- **KLEINE TRÄGERRAKETEN:  
Eine Europäische  
Perspektive**



# **KLEINE TRÄGERRAKETEN: EINE EUROPÄISCHE PERSPEKTIVE**

## ***SMALL LAUNCHERS: A EUROPEAN PERSPECTIVE***

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# 1 VORWORT DER PRÄSIDENTEN

Die französische Académie de l'air et de l'espace (AAE) und die Deutsche Gesellschaft für Luft- und Raumfahrt (DGLR) möchten einen gemeinsamen Beitrag zur Debatte über den Start von Kleinsatelliten mit kleinen Trägerraketen leisten. Ein gemeinsam veröffentlichtes Dossier liefert einen unvoreingenommenen Überblick über die derzeitige globale Situation, untersucht deren wichtigste Merkmale und spricht Empfehlungen für die Entwicklung dieses Sektors in Europa aus.

Viele Akteure haben Projekte für kleine Trägerraketen und neue Startplätze ins Leben gerufen, um jedem Kunden sowohl einen eigenen Start anbieten zu können als auch einen Preis, der im Wettbewerb mit den größeren Trägerraketen bestehen kann. In den Vereinigten Staaten wurden bereits Investitionen in Höhe von mehreren Hundert Millionen Dollar getätigt, oft mit Unterstützung staatlicher Stellen und neben zahlreichen technischen oder finanziellen Misserfolgen auch mit ersten Erfolgen. In Europa entstehen derzeit zahlreiche Projekte für künftige kleine Trägerraketen sowie für neue Startbasen.

Das von einer internationalen Arbeitsgruppe ausgearbeitete Dossier enthält eine Analyse der Marktaussichten in der Welt und in Europa sowie eine Bestandsaufnahme aller derzeit aus öffentlich zugänglichen Quellen bekannten bestehenden Projekte (Trägerraketen und Startplätze).

Das Dossier schließt mit einigen wichtigen Empfehlungen, deren Umsetzung Europa in die Lage versetzen könnte, im Bereich der Kleinsatellitenstarts weltweit führend zu bleiben. Die Vormachtstellung in diesem Sektor ist eine wesentliche Voraussetzung dafür, ein unabhängiger Hauptakteur in einem Wirtschaftsbereich mit vielversprechenden Perspektiven auf der Grundlage neuer Raumfahrtdienste und -anwendungen zu werden.

Die AAE und die DGLR veröffentlichen dieses Dossier mit dem alleinigen Ziel, die allgemeinen europäischen Interessen zu unterstützen. Beide sind bereit, diese Bemühungen in Zusammenarbeit mit den Akteuren, die dies wünschen, fortzusetzen.



**Prof. Rolf Henke**  
Präsident

A handwritten signature in black ink, appearing to read 'R. Henke'.

Deutsche Gesellschaft für Luft- und  
Raumfahrt (DGLR)



**Michel Wachenheim**  
Präsident

A handwritten signature in blue ink, appearing to read 'M. Wachenheim'.

Air and Space Academy  
(AAE)

## 2 ZUSAMMENFASSUNG

### 2.1 Bedarf und Markt

Die optimistischsten Prognosen gehen davon aus, dass im Laufe des kommenden Jahrzehnts weltweit etwa 4.000 Kleinsatelliten pro Jahr gestartet werden.

Dazu gehören Megakonstellationen mit hunderten bis tausenden von Satelliten für globale Breitbandverbindungen mit geringer Latenzzeit (Starlink, Kuiper, OneWeb, Telesat usw.), kleinere Konstellationen mit dutzenden bis hunderten von Satelliten für die Kommunikation mit niedrigen Datenraten (IoT-, ADS-B- und AIS-Anwendungen) und für Erdbeobachtung, die keine ultimativen radiometrischen Leistungen erfordern. Die meisten Konstellationen sind für eine optimale Abdeckung und wiederkehrende Beobachtungen oder zur Minimierung von Latenzzeiten konzipiert, das heißt, sie umfassen äquidistante Bahnebenen und mehrere Satelliten pro Bahnebene.

Abgesehen von den Megakonstellationen für die Breitbandkonnektivität, die angesichts der hohen Anzahl von Satelliten pro Bahnebene alle von mittelschweren oder schweren Trägerraketen gestartet werden, gehen realistische Prognosen von etwa 500 weiteren Kleinsatelliten pro Jahr aus, von denen die meisten eine Masse von weniger als zehn Kilogramm haben werden. Folglich dürfte die Menge an Kleinsatelliten mit einer Masse von weniger als 500 Kilogramm, die für Kleinträger auf dem freien Markt zugänglich ist, relativ gering sein und in der Größenordnung von fünf bis zehn Tonnen Gesamtmasse pro Jahr liegen.

Es gibt einen Markt für den Start von Kleinsatelliten in erdnahe Umlaufbahnen, wobei ein Teil davon aufgrund politischer Rahmenbedingungen und der vertikalen Integration eines Teils der US-Industrie für den Eigenbedarf bestimmt ist, sodass nur ein Bruchteil des Marktes kommerziell zugänglich ist.

Es wird unterschieden zwischen einem offenen Markt für große Anzahlen von Nanosatelliten mit geringer Masse, die sich im Besitz zahlreicher über die ganze Welt verteilter Betreiber befinden, und Startmöglichkeiten mit spezifischeren und anspruchs-

volleren Anforderungen, die von einigen wenigen privaten oder institutionellen (zivilen und militärischen) Kunden angeboten werden, wobei Letztere oft weniger offen für den globalen Wettbewerb sind.

Europa hat jedoch einen eigenen Bedarf für den Start von kommerziellen und institutionellen Kleinsatelliten, Letztere entweder für den Eigenbedarf oder für den Export. Dazu gehören zum Beispiel Satelliten von bis zu mehreren hundert Kilogramm für den zivilen institutionellen und den militärischen Einsatz. Bislang wurde noch kein Interesse an schnellen reaktiven Trägersystemen für Verteidigungszwecke („on demand“) bestätigt, doch die Nachfrage an Verteidigungsanwendungen entwickelt sich weiter, insbesondere in einigen europäischen Ländern, was darauf hindeutet, dass in naher Zukunft auch ein solcher Bedarf entstehen könnte.

Die Gesamtmasse der Kleinsatelliten, die von europäischen Betreibern für den Start zur Verfügung stehen, wird für den Zeitraum 2025 bis 2030 auf durchschnittlich 3,3 Tonnen pro Jahr geschätzt und ist Teil eines gesamten zugänglichen Startmarktes für europäische Träger, der auf insgesamt etwa 7,3 Tonnen pro Jahr beziffert wird.

Satelliten unter zehn Kilogramm stellen insgesamt nur eine geringe Startmasse dar. Die Masse der meisten einzelnen oder „gleichwertigen“ Satelliten von Konstellationen (Gesamtmasse pro Bahnebene), die von europäischen Betreibern geplant werden, liegt zwar unter 500 Kilogramm, aber die wenigen zwischen 600 und 900 Kilogramm stellen in der Summe eine erhebliche Startmasse dar.

Eine detaillierte Analyse der Massenverteilung zeigt, dass eine Startkapazität von weniger als 200 Kilogramm (Klasse der Mikro-Trägerraketen) für den Start der meisten geplanten europäischen Konstellationen unzureichend und dass für den Start aller Konstellationen eine Startkapazität von etwa 600 Kilogramm erforderlich wäre. Die Entwicklung von Mikro-Trägerraketen mit einer Kapazität von 150 Kilogramm kann aus verschiedenen Gründen interessant sein, zum Beispiel um neue Technologien zu erarbeiten, Innovationen zu fördern und junge Menschen für die Branche anzuwerben. Dieser Bereich könnte aber nur einen kleinen Teil des zugänglichen Startmarktes abdecken, weshalb die wirtschaftliche Nachhaltigkeit dieser Klasse von Trägern in Europa fraglich ist.

Die Analyse zeigt, dass der zugängliche europäische Startmarkt langsam und linear mit der Kapazität der Trägerrakete ansteigt, und zwar von etwa drei Tonnen pro Jahr bei einer Trägerkapazität von 500 Kilogramm auf etwas weniger als fünf Tonnen pro Jahr (einschließlich einiger europäischer Satelliten mit einer Masse von mehr als 500 Kilogramm) bei einer Kapazität von 800 Kilogramm. Dabei ist anzumerken, dass diese Proportionalität nicht weit über 1.000 Kilogramm hinaus extrapoliert werden kann. Eine wichtige Konsequenz ist, dass die potenzielle Zahl der Starts pro Jahr für alle Trägerkapazitäten bis etwa 800 bis 1.000 Kilogramm fast identisch ist. Für die geschätzte Größe des europäischen Marktes liegt die Größenordnung bei fünf bis sieben Starts pro Jahr. Mit dieser Kapazität könnte ein offener Weltmarkt von bis zu neun oder sogar zehn Tonnen pro Jahr erschlossen werden, wenn man außereuropäische Satelliten mit einem Gewicht von über 500 Kilogramm berücksichtigt, was acht bis zehn Starts pro Jahr entspräche und auch die Lücke, die durch die fehlende Verfügbarkeit der russischen Trägerrakete Rockot entsteht, weitgehend schließen würde.

**► Empfehlung n°1**

Aus der Perspektive des Bedarfs und des zugänglichen Marktes sollte sich Europa auf eine Kapazität von 800 bis 1.000 Kilogramm für eine kleine Trägerrakete konzentrieren, die die Familie der Ariane- und Vega-Trägerraketen erweitert und in der Lage ist, Satelliten mit einer Masse von mehr als 300 Kilogramm als Einzel- oder Primärnutzlast und/oder kleinere Satelliten als Sekundärnutzlast, Huckepack oder in Gruppen bei speziellen geteilten Starts zu starten.

**► Empfehlung n°2**

Die Entwicklung des Startbedarfs für neue europäische Sicherheits- und Verteidigungsmissionen im Weltraum sollte beobachtet werden, und die derzeitige Prognose für Kleinsatellitenstarts sollte Mitte des Jahrzehnts neu bewertet werden, um die mit dem Übergang zum neuen Weltraumzeitalter verbundenen Unsicherheiten zu verringern.

## 2.2 Aktueller Überblick über Kleinträgerraketen und Startplätze in der Welt

### 2.2.1 Trägerraketen

Bis heute (Stand Ende Juni 2021) wurde laut<sup>1</sup> die große Mehrheit der Kleinsatelliten von einigen wenigen<sup>2</sup> existierenden großen und mittelgroßen Trägerraketen gestartet, die mit den entsprechenden Vorrichtungen ausgestattet sind: Huckepack- und geteilte Starts für bis zu mehreren Dutzend Satelliten mit speziellen Separierungssystemen.

In den letzten Jahren wurden weltweit mehr als einhundert Projekte für den Start von Kleinsatelliten ins Leben gerufen. Die Liste entwickelt sich schnell weiter, viele Konzepte erscheinen und verschwinden regelmäßig.

Die Liste zeigt eine große Vielfalt an Startsystemarchitekturen: Mehrfachstarts durch große Trägerraketen (auch über die Internationale Raumstation ISS); kleine, spezielle, luftgestützte Trägerraketen (mit einem Start von einem Flugzeug oder einem Ballon); Trägerraketen, die vertikal vom Boden oder von einem Lastkahn aus abgefeuert werden, entweder wiederverwendbar (Rückkehr der ersten Stufe, Bergung per Fallschirm oder Hubschrauber, zweite Stufe im Gleitflug) oder als Einwegsystem, und sogar Projekte für den Start per Kanone oder Katapult vom Boden aus.

Die Projekte für kleine Trägerraketen sind auch in Bezug auf die Leistung recht unterschiedlich, von einigen Kilogramm in sehr niedrigen Umlaufbahnen (mit einer Technologie, die manchmal von Höhenforschungsraketen abgeleitet ist) bis zu etwa 500 Kilogramm in einen 500 Kilometer sonnensynchronen Orbit (SSO).

<sup>1</sup> *Smallsats by the Numbers, 2020*, Bryce space and technology.

<sup>2</sup> Falcon 9, Vega, Sojus, PSLV, Langer Marsch.



Einige wenige Projekte übertreffen diese Leistung und erreichen mehr als 1.000 Kilogramm in einer niedrigen Umlaufbahn.

Heute ist der technologische, industrielle oder finanzielle Reifegrad der Projekte oft recht gering und es stellt sich die Frage nach den Beweggründen für bestimmte Vorhaben: Souveränität, vorübergehender Trend, leicht zugängliche Anfangsfinanzierung, technologische Innovation, Förderung von Talenten, Entwicklung eines Ökosystems von Start-ups usw. Auf der anderen Seite ist in den letzten Jahren eine Reihe von Grundlagentechnologien zur Reife gelangt, die die Bereitstellung von Satelliten in der Umlaufbahn möglich und erschwinglicher machen, was vor einem Jahrzehnt noch nicht möglich war (zum Beispiel mithilfe von 3-D-Druck, Digitalisierung und Miniaturisierung). Dies könnte einen neuen „Goldrausch“ für Raumfahrtanwendungen auslösen, an dem sich viele Unternehmer beteiligen wollen.

Außerhalb Chinas haben nur wenige kleine Trägerraketenprojekte die Qualifikation oder den Status des Erstflugs erreicht (nicht immer erfolgreich). Beispiele hierfür sind Electron, Launcher One, Astra Rocket 3, Epsilon 2 und die staatlichen Trägerraketen Safir (Iran) und Shavit 2 (Israel).

Der Kreis der an den Projekten beteiligten Industrien ist sehr vielfältig. Er setzt sich zusammen aus staatlichen Einrichtungen (zum Beispiel aus Indien, China, Israel, Iran), Großindustriellen, die entweder direkt oder über Investitionen/Beteiligungen an neuen Unternehmen beteiligt sind, Zulieferern, die in der Wertschöpfungskette aufsteigen wollen, oder aus Start-ups.

Selbst bei den optimistischsten Annahmen scheint es eine Unstimmigkeit zwischen der Größe des voraussichtlichen Marktes, der Anzahl der Trägerraketenprojekte in der Welt und der Startrate zu geben, die erforderlich ist, um wettbewerbsfähige Produktions- und Betriebskosten zu erreichen. Selbst bei den günstigsten Marktprognosen bleibt ihre wirtschaftliche Nachhaltigkeit zweifelhaft, es sei denn, sie erhalten staatliche Unterstützung. Viele dieser Vorhaben werden höchstwahrscheinlich nicht zur Marktreife gelangen.

Die Zahl der in Europa konkurrierenden kleinen Trägerraketenprojekte und -standorte ist im Hinblick auf die technologische und finanzielle Innovation, den Wettbewerb und die Kreativität in der Anfangsphase der Entwicklung positiv zu bewerten. Trotz aufsehenerregender Kommunikationskampagnen verringert die derzeitige Verbreitung verstreuter Initiativen in Europa jedoch die Wahrscheinlichkeit eines nachhaltigen Erfolgs angesichts zahlreicher globaler Wettbewerber mit weit fortgeschrittenen Projekten, die von etablierten privaten und staatlichen Finanzierungskapazitäten unterstützt werden.

## Empfehlungen für künftige europäische Projekte

### ► Empfehlung n°3

Einige europäische Länder möchten eher auf ein großes Angebot an Startdiensten in der Welt zurückgreifen, andere bevorzugen eine europäische, unabhängige Startlösung für Kleinsatelliten. Die letztgenannten Länder sollten ihre zivilen und militärischen institutionellen Bedürfnisse und Ressourcen ermitteln und konsolidieren, um den Erfolg zumindest einer zufriedenstellenden Lösung zu gewährleisten.

**► Empfehlung n°4**

Die Raumfahrtagenturen sollten eine jährliche „Europäische Arbeitsgruppenkonferenz für kleine Trägerraketen“ organisieren, die das Ökosystem von kleinen Trägerraketenunternehmen, großen Trägersystemanbietern, Startdienstleistern, Investoren, Maklern, Agenturen und Kunden zusammenbringt, den Austausch von Informationen fördert und einen Mehrwert für das gesamte europäische Trägerraketen-Ökosystem und seine Akteure darstellt, einschließlich der Analyse,

- was die einzelnen Akteure tun und in welchen Bereichen sie zur Zusammenarbeit bereit sind,
- der Entwicklung des künftigen institutionellen Bedarfs (zivil und militärisch) sowie des kommerziellen Marktes.

**2.2.2 Startplätze**

In jüngster Zeit sind weltweit etwa 40 Projekte für Startanlagen entstanden, darunter mindestens zehn in Europa. Gründe dafür könnten ein Streben der Nationen nach Startautonomie sowie die Maximierung der Nutzung isolierter Gebiete oder geografischer Gegebenheiten, der Wunsch nach wirtschaftlicher Entwicklung und die erweiterte Nutzung bestehender Einrichtungen sein.

Die zahlreichen Projekte für Startplätze in Europa bieten gewisse Möglichkeiten, unterliegen aber auch Beschränkungen im Hinblick auf die Sicherheit, der Erreichbarkeit bestimmter Umlaufbahnen und den Kosten für den Zugang zu den Startplätzen.

**Empfehlungen für europäische Startplätze****► Empfehlung n°5**

Die Entwicklung europäischer Startplätze wird die Wettbewerbsfähigkeit der europäischen Anbieter für Startdienste mit kleinen Trägerraketen verbessern.

**► Empfehlung n°6**

Die Modernisierung des Raumfahrtzentrums Französisch-Guayana sollte den Ausbau der Kapazitäten für kleine Trägerraketen und die Verwertung von Stufen, die Überprüfung der Sicherheitsvorschriften und -mittel sowie die Senkung der Betriebskosten umfassen. Für eine erhebliche Zunahme der industriellen und Startkooperationen sollte die Verbesserung der Verfügbarkeit der Startanlagen ebenfalls berücksichtigt werden.

**► Empfehlung n°7**

Die Raumfahrtagenturen sollten aktiv an der Entwicklung und Bereitstellung von Informationen über die Kriterien und Bedingungen für neue europäische Startplätze mitwirken, damit diese das Raumfahrtzentrum in Französisch-Guayana effizient ergänzen können. Sie sollten den Informationsaustausch zwischen den Akteuren, einschließlich der Investoren, fördern und organisieren.

### ► Empfehlung n°8

In Anbetracht ihrer erheblichen Auswirkungen auf die Konstruktion von Trägerraketen und Startanlagen müssen die Flugsicherheitsvorschriften innerhalb Europas und in Übereinstimmung mit dem Rest der Welt überdacht werden.

## 2.3 Technologie und Leistung

### 2.3.1 Kleine Trägersysteme

Das Hauptziel eines neuen kleinen Trägersystems unterscheidet sich von den alten Zielen der Unabhängigkeit von anderen Ländern oder der technologischen Führung und besteht darin, sich auf die niedrigstmöglichen Gesamtbetriebskosten zu konzentrieren: die Kosten für den Transport des Satelliten in seine Umlaufbahn. Dies erfordert eine Verringerung der Anzahl der Stufen (luftgestützte Systeme, zweistufige vertikal gestartete Träger), eine Vereinfachung der Startvorgänge, eine teilweise Wiederverwendbarkeit, eine Konzentration der Produktionsressourcen, hohe Produktionsraten sowie innovative Konstruktions- und Herstellungsverfahren.

Auch wenn andere Konzepte derzeit entweder untersucht oder entwickelt werden oder bereits in Betrieb sind, gehören vertikal startende Systeme aufgrund der vorhandenen technologischen und industriellen Ressourcen und Infrastrukturen heute zu den technisch und finanziell tragfähigsten Systemen für das kommende Jahrzehnt in Europa. Später, nach ihrer Validierung, könnte die Verfügbarkeit fortgeschrittener Technologien, wie luftatmende Antriebe, geflügelte Systeme, ein höherer Grad an Wiederverwendbarkeit usw., alternative Optionen bieten.

### 2.3.2 Konzepte für kleine Trägerraketen

Angesichts des globalen Wettbewerbs wird die Kosteneffizienz ein entscheidender Erfolgsfaktor für künftige kleine Trägerraketen sein. Die Entwicklung einer wettbewerbsfähigen vertikal startenden Trägerrakete erfordert folgende Schlüsselmerkmale:

- die Begrenzung der Anzahl der Stufen auf zwei, mit einer zusätzlichen optionalen Stufe für bestimmte Fälle;
- die Verwendung einer einzigen Triebwerkstechnologie pro Trägerrakete und Erhöhung der Gemeinsamkeit zwischen den Stufen;
- die Optimierung der Masse der Trägerrakete durch drastische Verringerung des Anteils der Leermasse durch Verwendung leichter Metall- oder Verbundwerkstoffstrukturen, auch mit dem Risiko, dass die Zuverlässigkeit oder Verfügbarkeit zu Gunsten von niedrigen Preisen verringert wird;
- die Überarbeitung der europäischen Prozesse, Managementregeln, Konstruktions- und Qualifizierungsverfahren;
- die Entwicklung einer mehrfachen Wiederverwendung, zumindest für die Hauptstufe, wodurch ein Antriebssystem auf der Grundlage von Flüssigtreibstoffen erforderlich wird;
- die Konzeption des Startsystems mit dem Ziel eines einfachen und sicheren Starts.

Die Wiederverwendung der ersten Stufe verlangt eine spezielle Architektur der Trägerrakete (Stufung), die es ermöglicht, die Geschwindigkeit bei der Abtrennung zu begrenzen, um die für das Abbremsen erforderliche Energie zu verringern und die Erwärmung beim Wiedereintritt in die Atmosphäre zu begrenzen. Die gesteuerte Rückkehr zur Oberfläche (zum Boden oder zum Lastkahn) erfordert das Mitführen von Treibstoff und intelligenten Steuerungssystemen auf Kosten der Nutzlast und kann Triebwerke mit variablem Schub für die Rückkehr zum Startort notwendig machen. Die Bergung am Fallschirm, durch ein Netzsystem oder durch einen Hubschrauber verbraucht weniger Energie und ist mit einer einfacheren Triebwerksarchitektur vereinbar. In allen Fällen ist eine zusätzliche Ausrüstung an Bord und am Boden für die Bergung und Wartung unabdingbar.

### 2.3.3 Manövrierfähigkeit und Flexibilität in der Umlaufbahn

Die Verschiedenartigkeit der Nutzlasten (von einem bis 500 Kilogramm) und ihrer Umlaufbahnen (SSO und LEO in verschiedenen Höhen und Bahnneigungswinkeln) macht es wirtschaftlich unmöglich, für jeden einzelnen Kunden spezielle Starts anzubieten. Auch wenn einige Kunden spezielle Starts benötigen, um den Startzeitplan einzuhalten und die endgültige Umlaufbahn zu erreichen, und sich diese leisten können, werden die meisten Trägerraketenbetreiber bestrebt sein, den Füllungsgrad der Trägerrakete zu maximieren, und werden daher mehrere Satelliten starten müssen.

In einigen Fällen verfügen die Satelliten über eine spezielle Fähigkeit, an ihre endgültige Position zu gelangen. Jedoch erfordern doppelte oder mehrfache Starts zu verschiedenen Höhen und Umlaufbahnen Flexibilität an der Schnittstelle zwischen Trägerrakete und Nutzlast, um die endgültige Position für jeden Satelliten zu erreichen, begrenzt durch die Fähigkeit zur Höhen- und/oder Neigungsänderung. Dies wird durch optionale Systeme für den Transport der Nutzlast auf dem letzten Kilometer bewirkt, die zusätzliche optionale Stufen (Kick-Stufen), orbitale Transfermodule und Nutzlastseparationsvorrichtungen umfassen.

Eine Kombination aus angetriebenen Geräten und Nutzlastseparationsvorrichtungen ist zumindest bei mittleren und großen Trägerraketen möglich.

Weltweit werden mehrere orbitale Transfermodule für Trägerraketen aller Größen entwickelt, die eine Vielzahl von Antriebsarten, sowohl chemisch als auch elektrisch, nutzen. Einige europäische Unternehmen, traditionelle und neue, drängen auf den Markt für diese Systeme, die auch für Start-ups zugänglich sind. Derartig angetriebene Systeme bedürfen einer äußerst flexiblen Konstruktion, die sich an die Größe und die Umlaufbahn der Nutzlasten (zum Beispiel über die Größe der Tanks) anpassen lässt. Die Verwendung „grüner“ Treibstoffe wird einen Wettbewerbsvorteil darstellen, wenn nur eine kleine orbitale Transferkapazität erforderlich ist.

Wenn große orbitale Transferkapazitäten benötigt werden, könnte die Verwendung von elektrischen Antrieben mit relativ geringer Leistung (elektrothermisch) einen guten Kompromiss zwischen Masse, Leistung und Manöverdauer darstellen. Leider verfügt Europa in diesem Bereich über keine ausgereifte Technologie.

Die Sicherheitsvorschriften für den Start und den Orbitalbetrieb müssen bei der Entwicklung dieser Systeme berücksichtigt werden.

An Bord kleiner Trägerraketen führt die Verwendung unabhängiger Manövriermodule, unabhängig davon, ob sie mit chemischen oder elektrischen Antriebssystemen ausgestattet sind, zu einer erheblichen Erhöhung der Nutzlastmasse. Die Möglichkeit der gemeinsamen Nutzung von Elementen zwischen der Trägerrakete und ihrer zusätzlichen optionalen Stufe sollte in Betracht gezogen werden.

## **Empfehlungen für europäische Konzepte und Technologien für kleine Trägerraketen**

### **► Empfehlung n°9**

Es sollten zweistufige Vertikalstarts bevorzugt werden, bei denen die Stufen an den gewählten Bergungs-/Wiederverwendungsmodus angepasst sind und die Präzision der Orbitinjektion durch Schubmodulation (elektrische Turbopumpe oder andere Vorrichtungen) gewährleistet ist. Das Konzept der Trägerrakete sollte flexibel/modular sein und eine Weiterentwicklung im Laufe der Zeit ermöglichen.

### **► Empfehlung n°10**

Die technologische Entwicklung in den Bereichen Antrieb (LOx-CH<sub>4</sub>, Hybridtreibstoffe, „grüne“ Treibstoffe), leichte Strukturen (aus kohlenstoffaserverstärktem Kunststoff (CFK) oder Metall) und verschiedenen Bergungsmodi muss beschleunigt werden, einschließlich des Einsatzes von Demonstratoren im realen Maßstab. Sobald sie für kleine Trägerraketen validiert sind, können diese Technologien an mittlere und schwere Trägerraketen angepasst werden.

### **► Empfehlung n°11**

Um wettbewerbsfähige Trägerraketen zu entwickeln, müssen die in Europa angewandten Konstruktions- und Qualifikationsregeln dringend überarbeitet werden<sup>3</sup>.

### **► Empfehlung n°12**

Die Bandbreite möglicher Dienste, die von innovativen Kick-Stufen und Systemen für die Manövrierfähigkeit im Orbit angeboten werden, sollte untersucht werden, da sie für die Betreiber von Startdiensten einen entscheidenden Vorteil darstellen können. Solche Dienstleistungskapazitäten sollten sowohl für kleine Trägerraketen als auch für Ariane 6 und Vega-C entwickelt werden.

3 Der Vergleich mit erfolgreichen Projekten und die Rückmeldungen aus europäischen Erfahrungen müssen besser genutzt werden, zum Beispiel in folgenden Bereichen: Konstruktionsindizes für Triebwerke und Stufen, insbesondere für die Oberstufe, statistische Analyse der Belastungsdauer und der Belastungsstufen, Ermittlung von Reserven zur Verringerung der Testbelastungen für Nutzlasten oder Trägerraketenentwicklungen, Kalibrierung der thermischen, strukturellen und antriebstechnischen Reserven, Minimierung von Unbekannten, Akzeptanz von Winden in großer Höhe usw.

**► Empfehlung n°13**

Die Entwicklung „grüner“ oder ungiftiger Treibstoffe und elektrothermischer Antriebstechnologien (oder gleichwertiger Technologien unter dem Gesichtspunkt der Leistung: spezifischer Impuls und Schub für eine gegebene elektrische Eingangsleistung) sollte in Europa vorangetrieben werden.

## 2.4 Kosten und Finanzierung

Wir gehen davon aus, dass das Geschäft mit dem Start von Kleinsatelliten in Zukunft sehr viel offener für den Wettbewerb sein wird als das derzeitige Geschäft mit mittelschweren und schweren Trägerraketen, bei denen der Großteil des Marktes durch staatliche Institutionen gebunden oder geschützt ist.

### 2.4.1 Entwicklungsphase

In der Entwicklungsphase sind die Budgets für die Technologiedemonstration und die frühe Produktion bei kleinen Trägersystemen aufgrund ihrer Größe erschwinglicher als bei größeren Trägersystemen. Die geringere Größe sorgt auch für niedrigere Kosten von Ausrüstung und Komponenten und ermöglicht eine intensive Nutzung des 3-D-Drucks, was wiederum die Anpassung des Entwicklungsprozesses an die Zyklen Entwurf – Fertigung – Test – Fehler – Entwurfsanpassung ermöglicht.

Damit eignen sich kleine Trägerraketen für eine private Finanzierung, wobei die Finanzierung durch Risikokapital der Serien A bis D auf die Fortschritte bei der Technologiedemonstration sowie bei Boden- und Flugtests abgestimmt ist.

Die Technologiedemonstration durch erfolgreiche Flüge muss durch eine Industrialisierungsphase ergänzt werden, in der die Fähigkeit zur Bereitstellung eines wettbewerbsfähigen und zuverlässigen Startdienstes nachgewiesen wird. Auch wenn mit flugerprobten Konstruktionen bereits 2004 (Virgin) und 2006 (Rocket Lab) begonnen wurde, haben solche Projekte Schwierigkeiten, eine nachhaltige Betriebsphase zu erreichen: Zwei erfolgreiche Flüge für Launcher One und 20 Flüge in vier Jahren für Electron, darunter drei Fehlschläge, sind noch weit von den manchmal prognostizierten wöchentlichen Starts entfernt.

Die meisten Entwürfe entwickeln sich im Laufe ihrer Planung weiter, sowohl in Bezug auf die Technik als auch auf das Finanzierungskonzept. Es ist interessant zu sehen, dass die am weitesten fortgeschrittenen Projekte für kleine Trägerraketen (Rocket Lab, Astra, Relativity, Firefly...) nach zusätzlicher Finanzierung für die Entwicklung größerer Trägerraketen suchen, manchmal sogar noch vor dem erfolgreichen Flug der ersten kleinen Trägerrakete. Dies war auch der Weg, den SpaceX eingeschlagen hat: zunächst Falcon 1, dann Falcon 1e, dann Falcon 9 und ihre zahlreichen Weiterentwicklungen zur Erhöhung der Nutzlastkapazität. Diese Situation kann aus einem besseren Verständnis des Marktes resultieren, aber auch aus dem Streben nach höherer Rentabilität, wobei die kleine Trägerrakete ein Wegbereiter für den Zugang zu umfassenderen Startdiensten und Raumfahrtanwendungen ist.

In den USA gibt es eine Vielzahl von Finanzierungsmodellen, bei denen häufig mehrere Quellen kombiniert werden. Öffentliche Mittel werden oft in verschiedenen Formen eingesetzt: freier Zugang zu Kompetenzen und Einrichtungen, direkte Finanzierung, finanzielle Vorleistungen von Agenturen. Die private Förderung erfolgt durch Eigenkapital, das von großen Industrieunternehmen (zum Beispiel Lockheed Martin in Rocket Lab) oder von Risikokapitalfonds bereitgestellt wird, wie zum Beispiel die 500 und 650 Millionen US-Dollar, die Relativity erhalten hat. In jüngster Zeit gehen einige Unternehmen durch Börsengänge oder sehr umfangreiche SPACs<sup>4</sup> an die Börse, wie die erwarteten 500 Millionen US-Dollar durch Astra, 320 Millionen US-Dollar durch SPAC und 470 Millionen US-Dollar Eigenkapital für Rocket Lab.

Obwohl die privaten Finanzierungsangebote in Europa in den letzten Jahren zugenommen haben, bleiben sie weit hinter den Möglichkeiten in den USA zurück, sowohl was den Umfang als auch was die Vielfalt der Finanzierungsquellen betrifft.

Die öffentliche und private Zusammenarbeit bei der Finanzierung neuer Initiativen entsteht derzeit in Europa – zum Beispiel durch die Europäische Kommission (Horizon 2020) und die Europäische Weltraumorganisation ESA oder die Beispiele ArianeWorks und Isar Aerospace in Frankreich und Deutschland –, bleibt aber bisher ohne übergreifende Koordination verstreut.

Es wurden zwar Entwicklungskosten in Höhe von 100 bis 500 Millionen US-Dollar genannt, doch noch kein Projekt wurde zu den angekündigten Budgets industrialisiert. Die Kosten hängen dabei stark von der Erfahrung der Teams, den Systemkonzepten und der Wahl der Technologie, dem Zugang zu vorhandenen Kompetenzen und Testinfrastrukturen sowie den geltenden Qualifikations- und Sicherheitsvorschriften ab.

Ungeachtet dessen scheinen die Entwicklung und der Erstflug einer Kleinstträgerrakete, die 150 bis 200 Kilogramm Nutzlast in eine LEO-Umlaufbahn bringt, zu Kosten in der Größenordnung von 150 bis 200 Millionen Euro machbar zu sein. Das entsprechende Budget für eine kleine Trägerrakete, die bis zu 500 Kilogramm Nutzlast transportieren kann, würde etwa 400 Millionen Euro betragen sowie 500 bis 800 Millionen Euro für eine Trägerrakete, die 800 bis 1.000 Kilogramm Nutzlast transportieren kann.

Für die Serienproduktion sind jedoch zusätzliche Investitionen erforderlich, die von der Produktionsrate, der industriellen Organisation, der Verfügbarkeit der Startrampe(n) und staatlichen Auflagen abhängen.

## 2.4.2 Produktions- und Nutzungsphase

Im Hinblick auf die Trägerraketen sind die Preise für Huckepack- oder geteilte Starts auf einer mittelschweren oder schweren Trägerrakete nach wie vor die wettbewerbsfähigsten Angebote, die zwischen 5.000<sup>5</sup> und 10.000 US-Dollar pro Kilogramm Nutzlastmasse liegen, vorausgesetzt, die Anforderungen an die Wahl der Umlaufbahn, die

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4 Special Purpose Acquisition Companies.

5 Der sehr niedrige Preis von 5.000 US-Dollar pro Kilogramm an Bord der Falcon 9 gilt für Satelliten mit einer Masse von mindestens 200 Kilogramm. Das bedeutet, dass für Satelliten mit einer Masse von weniger als 200 Kilogramm ein Startadapter (Dispenser) für die Integration mehrerer Satelliten benötigt wird.



Einschussgenauigkeit und der Starttermin haben für die Kunden keine Priorität. Die von Vermittlern, Unternehmen für kleine Nutzlasten (Spaceflight Industries, Momentus, Exolaunch ...) oder Startdienstleistern vorgeschlagenen Entwicklungen von Orbitalmanövrier- und -vorrichtungen können eine potenzielle Verbesserung der gelieferten Bahngenauigkeit bieten, was allerdings mit zusätzlichen Kosten verbunden ist.

Kleine, zweckbestimmte Starts bieten eine größere Verfügbarkeit und Anpassungsfähigkeit an Kundenanforderungen, sei es in Bezug auf Leistung, Sicherheit oder Vertraulichkeit. Der üblicherweise genannte Preis von fünf Millionen US-Dollar pro Start (bei weniger als 500 Kilogramm Nutzlast) bleibt ein Ziel, das im Allgemeinen mit sehr hohen prognostizierten Startraten von 50 bis 300 (Astra) Starts pro Jahr verbunden ist. Die Kostenschätzungen scheinen generell sehr optimistisch, und realistische Zahlen sind schwer zu finden. Mehrere Anbieter von Trägerraketen profitieren von frühen institutionellen Aufträgen (in der Regel aus den USA) im Bereich von fünf bis 15 Millionen US-Dollar für sehr kleine Nutzlasten.

Die wirtschaftliche Nachhaltigkeit der angestrebten Preise muss noch bestätigt werden. Das 2006 gegründete Rocket Lab rechnet damit, frühestens 2024 einen positiven Cashflow zu erzielen, wobei ein erfolgreicher Börsengang im Jahr 2021 vorausgesetzt wird<sup>6</sup>.

Eine realistischere Produktionsrate von etwa zehn pro Jahr könnte das Stückkostenziel infrage stellen und macht es schwierig, die Investition allein mit dem Kriterium der Rentabilität zu rechtfertigen, selbst wenn man die Amortisation der Fixkosten für Produktion und Startmittel außer Acht lässt. Daher sollten auch andere Kriterien berücksichtigt werden, wie die Entwicklung von Ökosystemen, der Einstieg in weiter ausgebaute Raumfahrtendienste (SpaceX, Rocket Lab), die Befriedigung eines institutionellen Eigenbedarfs, die technologische Unabhängigkeit, die Herausbildung von Unternehmerteilgeist und die Begeisterung für die Wissenschaft.

## Empfehlungen für die Finanzierung in Europa

### ► Empfehlung n°14

Forcierung der Entwicklung des europäischen Ökosystems für öffentliches und privates Kapital.

### ► Empfehlung n°15

Der Ansatz einer öffentlich-privaten Partnerschaft könnte ein praktikables Erfolgsmodell sein, erfordert jedoch die Zusammenarbeit zwischen beiden Arten von Akteuren.

## 2.5 Schlussfolgerung

Die gemeinsame Arbeitsgruppe der französischen Luft- und Raumfahrtakademie (AAE) und der Deutschen Gesellschaft für Luft- und Raumfahrt (DGLR) ist der Ansicht, dass im

<sup>6</sup> Rocket Lab internet site, May 2021.

Zusammenhang mit dem zunehmenden Ausbau neuer Raumfahrtanwendungen und der Wirtschaft sowie der Entwicklung der Satellitentechnologien hin zu kleineren Raumfahrzeugen ein Bedarf an kleinen Trägerdiensten in Europa besteht.

Obwohl der Weltmarkt relativ begrenzt ist und einem starken Wettbewerb unterliegt, liegt es im strategischen Interesse Europas, dafür zu sorgen, dass mindestens ein europäisches Projekt für eine kleine Trägerrakete sobald wie möglich verwirklicht wird, um den europäischen Bedarf an leistungsfähigen Startdiensten für Kleinsatelliten zu decken, die bei realistischen Startraten wettbewerbsfähig sind.

In Europa sollte eine Trägerrakete der 800-Kilogramm-Nutzlastklasse in einen 500 Kilometer sonnensynchronen Orbit (SSO) entwickelt werden, die über eine Kapazität für Orbitalmanöver verfügt und eine Aufteilung der Startkosten auf mehrere Satelliten ermöglicht. Eine Rate von etwa acht bis zehn Starts pro Jahr könnte erreicht werden, indem sowohl der Start aller kompatiblen europäischen institutionellen Satelliten garantiert wird als auch ein Teil des zugänglichen kommerziellen Marktes für Kleinsatelliten und einige Einzelsatelliten über 500 Kilogramm gestartet werden können. Die Kosten für die Entwicklung des Trägersystems, einschließlich der Produktions- und Startanlagen, liegen im Bereich von 500 bis 800 Millionen Euro und hängen stark von den technologischen Optionen, der gewünschten Produktionsrate, den von den Behörden auferlegten Bedingungen und den Konstruktions-, Sicherheits- und Zertifizierungsvorschriften ab. Für die Entwicklungsphase wird höchstwahrscheinlich eine institutionelle Unterstützung in Form von Teilfinanzierung (PPP), einem freien Zugang zu Bodeneinrichtungen und frühzeitig garantierten Ankeraufträgen erforderlich sein. Mit einem zweistufigen vertikal startenden Träger mit Flüssigtreibstoff, der mit mehreren optionalen Orbitalmanövriersystemen kompatibel ist, sollte diese Trägerrakete teilweise wiederverwendbar sein, zumindest für die erste Stufe, sofern dies wirtschaftlich gerechtfertigt ist. Bei der Entwicklung sollten Startkosten in der Größenordnung von zehn Millionen Euro angestrebt werden, um attraktive Preise zu erzielen.

Darüber hinaus könnte eine Trägerrakete der 150-Kilogramm-Klasse für eine 500-Kilometer-SSO-Umlaufbahn entwickelt werden, die auf Abruf Starts in eine präzise Umlaufbahn ermöglicht. Die Konstruktion einer solchen Trägerrakete (Entwicklungskosten in der Größenordnung von 150 bis 200 Millionen Euro), bei der mehrere technologische Innovationen (Antrieb, Strukturen, Herstellungsverfahren) miteinander konkurrieren, scheint mit einer privaten Finanzierung vereinbar zu sein, die die Schaffung eines Ökosystems europäischer Raumfahrt-Start-ups unterstützt. Die wirtschaftliche Nachhaltigkeit der Nutzung solcher Trägerraketen muss noch bestätigt werden, aber es wird die Möglichkeit geben, validierte Technologien in zukünftige größere Trägerraketen zu integrieren.

Die Entwicklung optionaler Servicefunktionen für die Manövrierfähigkeit in der Umlaufbahn sollte für Trägerraketen aller Größen, einschließlich Ariane 6 und Vega-C, erfolgen, um mehrere Kleinsatelliten mit verbesserter Genauigkeit in verschiedene Umlaufbahnen zu bringen.



# ***SMALL LAUNCHERS: A EUROPEAN PERSPECTIVE***

*Full text and annexes  
in English*

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## 3 INTRODUCTION

*In order to compile a dossier on Small Launchers, the Académie de l'Air et de l'Espace (AAE – Air and Space Academy) and the Deutsche Gesellschaft für Luft- und Raumfahrt (DGLR) set up a working group of 17 international experts: German, French, Italian and Spanish (listed in Annex 1), under the mandate presented in Annex 4.*

*The group based its work on existing documents, mainly from presentations, publications, conferences, communications and websites, on hearings of some representative actors in the field of satellites and launchers, and on the analyses and numerous working sessions of the group's experts.*

*The dossier includes a standalone Executive Summary that provides a clear overview of the content of the whole dossier, including all recommendations and the conclusion almost in full.*

*The main body of the dossier is made up of four chapters, each concluding with its own recommendations, which can be read independently:*

- *the outlook for the small satellite launch market for the 2025-2030 period;*
- *a presentation of small satellite launchers and launch sites around the world;*
- *architectural principles and technologies;*
- *main cost factors and financing schemes.*

*The conclusion presents the opinion of the AAE and DGLR on the future of small launchers in Europe.*

*The annexes provide additional information, including detailed analyses of the current and potential market, the principles of orbital maneuvers and launcher projects around the world.*

## 4 SMALL SATELLITE LAUNCH MARKET BY 2025-2030

### 4.1 Introduction

*The business case for small launchers is driven by trends in the market of small satellites (< 500 kg, see Annex 3: Definition of small satellites categories) and the associated evolution of launch needs and requirements.*

*A steep growth in the number of small satellites (< 500 kg) available for launch can already be observed and is forecast to continue as a trend over the next decade. However, the share of the additional launch market actually accessible to small launchers must be carefully assessed, given that small satellites can also be delivered to orbit by medium or heavy launchers as “piggyback<sup>1</sup>” or “rideshare<sup>2</sup>” launches, which has been the case for most of the cubesats weighing less than 10 kg that have proliferated in the past decade.*

*This section provides an assessment of the world small satellite market and regional contributions, based on historical and forecast information available from internet sites or presentations from market analysis firms, service companies, industries and agencies<sup>3</sup> in the space sector and direct contacts with experts.*

*The results were interpreted in the light of the working group members’ knowledge, particularly to derive implications for launch markets, taking into account the mass distribution of satellites and the configurations of planned constellations.*

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1 A satellite is piggyback launched when launched as a secondary or auxiliary payload at the time and into the orbit dictated by a primary payload.

2 A satellite is rideshare launched when it is part of a cluster of different satellites, none of which is primary payload.

3 As an example, Ms Lafaye from CNES was interviewed on the market for nanosatellites and its forecast evolution.

*The selected approach consists of compiling and cross-referencing small satellite market figures available from market analysis firms, via the internet<sup>4</sup> or conference presentations, with information also available on the estimated mass of individual satellites and the configurations of contributing constellations, in order to estimate and characterise the distributions of satellite mass becoming available for launch worldwide and in Europe, identified as the drivers of relevant launch markets.*

*The market share accessible to European small launchers was then more specifically analysed, in view of the specific characteristics of the forecast European small satellite market and the existence of captive launch markets in other spacefaring nations, to arrive at recommendations on the most promising capacity for a European launcher, from a European need and market perspective.*

*Annex 5 provides complementary information.*

## **4.2 Small satellites launch market**

*The period 2019-2028 is seen as the first decade of the “New Space” era, ushered in by enhanced capacities of small satellites and miniaturised payloads, and the new business opportunities offered by Low Earth Orbit constellations based on low-cost serial production.*

*This includes mega-constellations of hundreds to thousands of mini satellites for global, low latency broadband connectivity (e.g. Starlink, Kuiper, OneWeb, Telesat, etc.), smaller constellations of tens to hundreds of satellites for low-rate communications (IoT, ADS-B and AIS applications) and Earth observations not requiring ultimate radiometric performances. Most of the constellations are “organised” to optimise coverage and revisit of observations or reduce latency in connectivity, i.e. involve equidistant orbit planes and several satellites per plane, which drives requirements for efficient launch services.*

*New Space constellations and their services are integrated into large economic ecosystems including cloud, high performance computing and artificial intelligence in a global business perspective, which has triggered vertical integration in US Industry, from launcher to broadband connectivity mega-constellations and cloud services, such as Blue Origin-Kuiper-Amazon, SpaceX-Starlink-Google, etc.*

*Small satellites have also become an enabler for faster in-orbit demonstration of technology and service capabilities, triggering a different approach to risk and enabling the low-cost deployment of some science missions, e.g. based on swarms.*

*Although the objectives of New Space operators are generally of a commercial nature, one key success factor for most of them remains the support of national governments, through government-funded R&D, aggressive space or commercial policies, or governments acting as anchor tenant customers of targeted data and services. One*

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<sup>4</sup> Most of the information found on the internet and used as input to the launch market assessment originates from Euroconsult, Northern Sky Research, Price Waterhouse Cooper, Bryce.

*consequence is that the corresponding launches of small satellites are largely captive, which is not the case in Europe.*

*Moreover, SpaceX is offering very low-cost rideshare launch opportunities to operators of small satellites during the initial deployment of its Starlink constellation, thus capturing a significant share of the non-captive market in this period.*

*The current decade is transitional, since it combines fast, unprecedented development with large uncertainties regarding economic sustainability, both of which factors impact the launch service demands in the longer term.*

*This decade will see completion of the initial deployment of mega-constellations for broadband connectivity and of smaller constellations of satellites for high resolution optical and radar imagery, weather and climate monitoring and low-speed communications, thus bringing maturity to the applications of these constellations and insight as to their added value to citizens, the digital economy and the security of spacefaring nations.*

*As the number of small satellites in orbit grows accordingly, the decade should also feature the development of emerging missions for active space debris removal and other in-orbit services, triggering potential additional needs for launch services.*

*The main source of uncertainties is the sustainability of the business models and plans of New Space operators, some competing on the same markets. The first results will drive the strategies for refreshment and evolutions of constellations and the associated demand for launch services.*

*Likewise, in view of the lower ownership costs of small satellite systems, more space programmes may emerge on the initiative of service companies dedicated to specific applications or even on the initiative of specific users wishing to have their own space system.*

*Other sources of uncertainty are in the field of defence and security of space assets. These fields are expected to become more prominent, especially in countries such as the US, China and Russia, but the actual scope and magnitude of dedicated efforts involving small satellites and the specific launch requirements are largely undetermined.*

*Various prototype developments should appear in Europe, to assess the potential use of small satellites for defence and security purposes and the associated launch requirements, like in the US.*

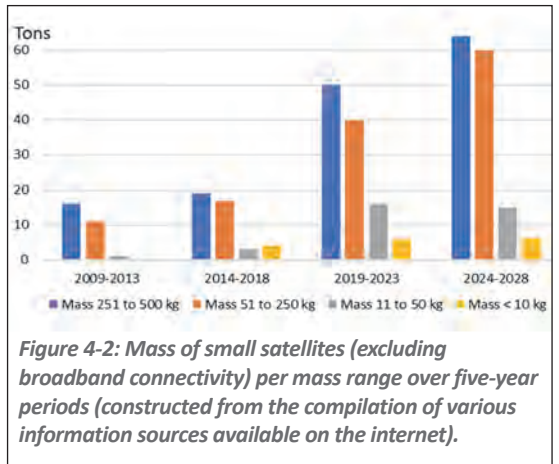
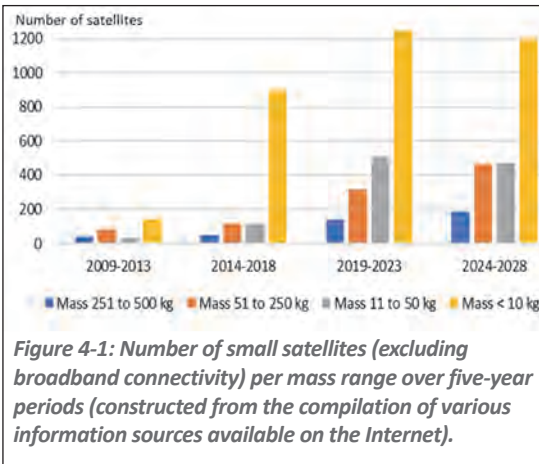
*The evolution of launch requirements and potentially specific constraints for new European security and defence space missions should be monitored, in order to react on the launcher development side. More generally, the current forecast for small satellite launches presented hereafter should be reassessed in the middle of the decade, to narrow down the inherent uncertainties of the ongoing transition to the New Space era.*

*The forecast for the coming decade shows that the announced growth in the number of broadband telecommunications mini-satellites of mega-constellations represents around 50% of all satellites to be launched (see Annex 5.2).*

*The current observation is that all current projects of mega-constellations for broadband communications are based on satellites with a mass above 150kg, which will be*

launched by medium or heavy launchers, whether for initial constellation deployment or renewal of satellites in each orbital plane<sup>5</sup>. It is also recalled that most of these launches will be captive<sup>6</sup>.

Figure 4-1 shows an analysis of the number of satellites launched or planned for launch worldwide in each mass range over the period 2009-2028, **excluding broadband satellite constellations**. Figure 4-2 depicts the resulting masses of small satellites launched or planned for launch, showing a total mass of about 26 tons per year planned for launch in the decade 2019-2028, of which nanosatellites and microsatellites with a mass of under 30 or 50 kg represent only a very small fraction. The vast majority of small satellites are expected to be launched into low Earth orbits.

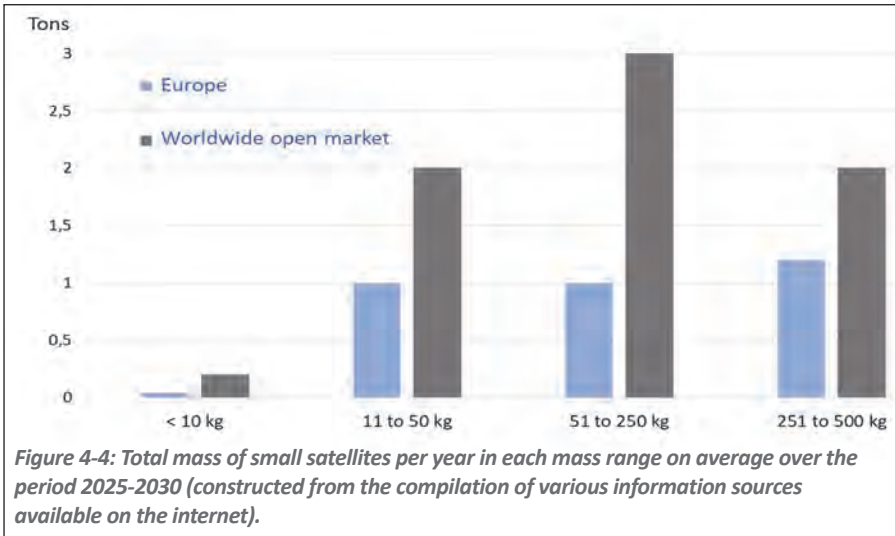
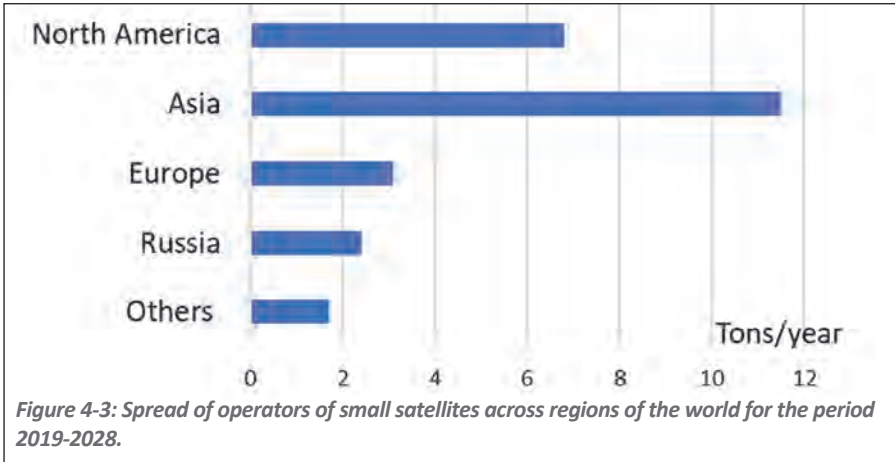


Operators are spread across different regions of the world with a significant share taken by Asia, particularly China, with captive launches (see Figure 4-3).

Based on scenarios of commercial, governmental and university missions in different countries of the world, the order of magnitude of the launch market for small satellites from European operators can be estimated on average per year at about 3.3 tons and the open (including European) launch market for European launchers at about 7.3 tons (See Figure 4-4).

5 The current launches of the Starlink and OneWeb constellations are made by clusters of at least 8 or 10 and up to 64 satellites with medium or heavy launchers. Future constellations for broadband communications whether based on mini satellites or not will likely be launched in the same way (such as Kuiper constellation with Atlas 5). Therefore, the minimum mass per launch is, or will be, in probably all cases, greater than 1,000 kg.

6 Captive launch means that the launch is not open to competition. Examples: Starlink with SpaceX launches, (vertical integration), Russian and Chinese satellites launched with national launchers.



### 4.3 Characterisation of the small satellite launch market

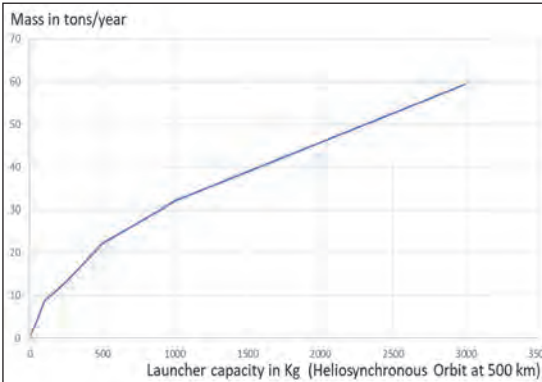
Various characteristics of the small satellite launch market are discussed in this chapter, again excluding mega-constellations for broadband telecommunication.

#### 4.3.1 Distribution of the satellite launch mass per launcher capacity

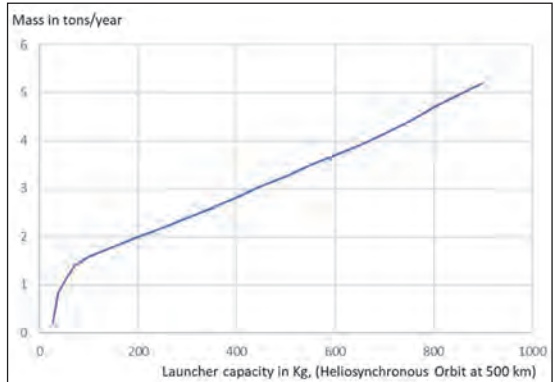
Market analyses for the current decade predict that the total annual mass of low Earth orbit satellites with a unit mass of less than a given launcher capacity is growing rapidly in the range of small satellites and continues to grow significantly, although at a slower



pace, for satellites from 500 to 3,000 kg (see Figure 4-5 for the annual world launch market up to 3,000 kg and Figure 4-6 for the European market up to 900 kg).

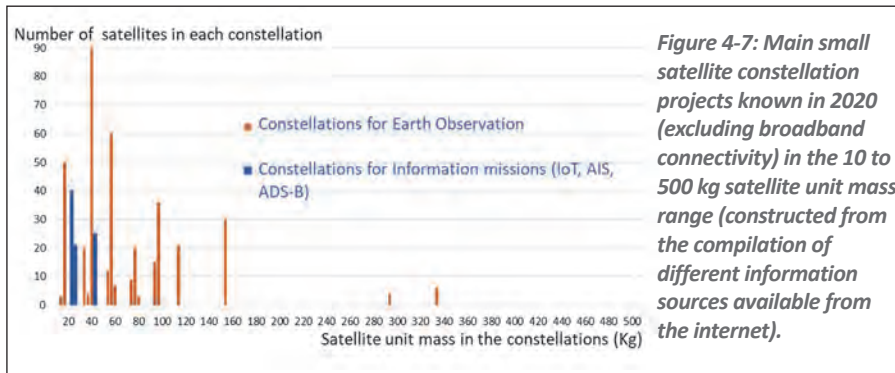


**Figure 4-5: Potential worldwide launch market as a function of launcher capacity.**



**Figure 4-6: Accessible European launch market as a function of launcher capacity, assuming launches of individual satellites.**

The majority (typically 60%) of these satellites for the next decade are expected to be in constellations. From the observation of the main small satellite projects identified in 2020, the constellations with more than 5 to 10 satellites use satellites of less than 100 kg for Earth observation applications, mostly in sun-synchronous orbits, and less than 50 kg for Information (IoT, AIS, ADS-B)<sup>7</sup>, as shown in Figure 4-7.



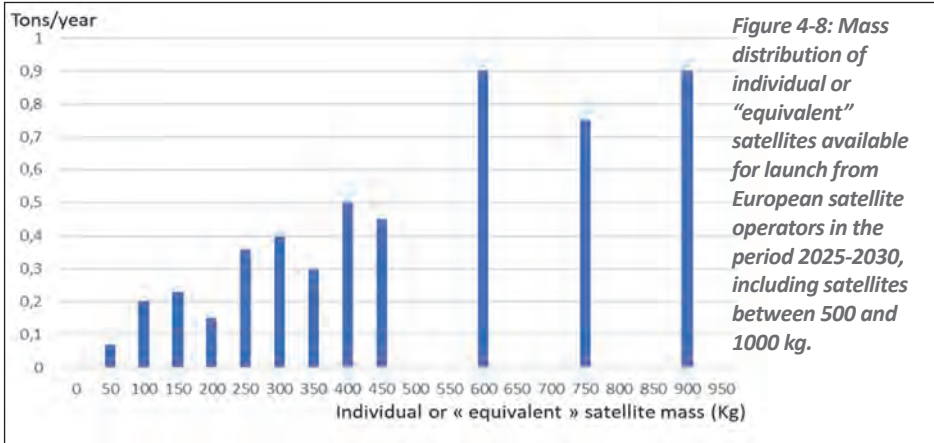
**Figure 4-7: Main small satellite constellation projects known in 2020 (excluding broadband connectivity) in the 10 to 500 kg satellite unit mass range (constructed from the compilation of different information sources available from the internet).**

Constellations based on nanosatellites <10 kg are not shown in Figure 4-7, and those initiated by China are missing as well, because of insufficient available information.

After the experimentation and validation phases, constellations are generally deployed by orbit plane, each containing several satellites. Since all or a subset of satellites of a plane are launched together in one launch, they can be considered as a single "equivalent satellite" from the launcher point of view. Constellations are expected to be

<sup>7</sup> IoT is Internet of Things, AIS is Automatic Identification System, an automatic tracking system used for vessel traffic services, ADS-B is for Automatic Dependent Surveillance -Broadcast used for air traffic management services.

maintained in the same manner after their initial full deployment. These groupings into “equivalent satellites” are illustrated for the forecast accessible European market for the period 2025-2030 in Figure 4-8.



The typical distribution of the annual mass of individual and “equivalent” (when applicable) satellites up to 1,000 kg presented in Figure 4-8 takes into account the configurations of small satellite constellations, i.e. the mass of each satellite, the number of orbit planes and the number of satellites per plane. It shows that the majority of “equivalent” or individual satellites available for launch from European operators have a mass below 500 kg, and that the few having a mass between 600 kg and 900 kg together represent a significant launch mass.

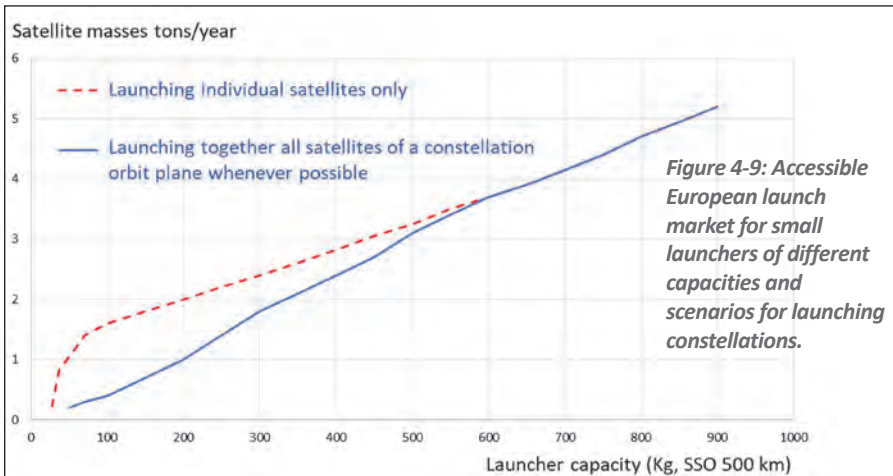


Figure 4-9 shows, from a launcher perspective, the annual total mass of satellites available for launch from European satellite operators for a given launcher capacity, if one considers:

- *launching only individual satellites (red dotted curve) and*
- *launching “full equivalent” satellites in the case of a constellation, i.e. all satellites in one orbit plane which is the most efficient approach for the operator, and individual satellites otherwise (blue plain curve).*

*If one assumes that the launch cost per kilogramme decreases with increasing launcher capacity, as observed across the market, the comparison of both curves shows that:*

- *a launcher capacity below 200 kg (micro-launcher class) is inadequate for launching most full “equivalent” satellites (gap between both curves);*
- *a launcher capacity above 600 kg becomes suitable for launching full “equivalent” satellites of all planned constellations of small satellites (both curves converge around 600 kg).*

*It also shows that the accessible launch market for equivalent and individual satellites increases slowly and linearly with launcher capacity. As a result, a launcher capacity of 350 kg would open up a potential European market of around 2 tons per year, while a capacity of 800 kg would give access to a market of a little less than 5 tons per year, including “full equivalent satellites” of all planned small satellite constellations and some individual satellites above 500 kg. It is however important to note that extrapolating both curves to higher launcher capacity, i.e. well above 1,000 kg, would be misleading. This is because, considering their actual mass, equivalent satellites of planned small satellite constellations or individual satellites up to 1,000 kg could no longer expect to be primary payloads of much bigger launchers like VEGA-C.*

*An important consequence of the proportionality between the launcher capacity and the European launch market accessible by this capacity is that the potential number of launches per year for European customers is almost identical for any launcher capacity up to 800 to 1,000 kg, in the order of five to seven launches per year for the estimated size of the European market.*

### **4.3.2 Acceptability of piggyback or shared launches**

*Due to economy of scale effects, the launch price per kilogram of payload generally decreases as launcher capacity increases. However, when many satellites are launched in a cluster, most of them are not injected into their preferred orbits, unless most of the satellites populate a single constellation orbital plane. In other terms, with respect to their preferred orbits, the “level of heterogeneity” of the small satellites launched together increases on average with the capacity of the launcher.*

*Statistically, nanosatellites, and even micro-satellites, appear to be the most flexible with respect to orbital constraints imposed by cluster launches. The launch market accessible to micro launchers in the 150 kg class is therefore particularly subject to competition from cluster launches by medium and heavy launchers.*

*Likewise, satellites launched for educational purposes, technological experiments, testing of the first versions of satellites with an operational vocation or market initialisation, are likely to be the least demanding with regard to their preferred orbits.*

Conversely, the initial deployment and replacement of organised constellations of small satellites need to fulfil precise orbital requirements, as do the launches of micro and mini-Earth observation satellites supporting operational information services.

The grouped launch of all or a subset of the satellites in each plane of an organised<sup>8</sup> constellation is highly desirable for the sake of cost efficiency. Therefore, the constellation market accessible to very small launchers is in practice limited to constellations of nanosatellites.

The acceptability of launching small satellites as passengers or in shared launches tends to decrease when the capacity of the launcher increases substantially. This is because the orbital constraints of the primary payload(s) are increasingly imposed on small satellites, with no compromise possible onboard medium and heavy launchers. However the level of acceptability is expected to increase when launch services based on medium or heavy launchers offer final transportation to the desired orbits by means of orbital transfer modules, which is possible if the desired orbits are not too far from the orbit of the primary payload.

## 4.4 Target capacity for a small European launcher

### 4.4.1 Need to bridge a critical gap in the European launcher family

With VEGA-C and Ariane-6, Europe, through ESA, is developing its next generation of medium and heavy launchers, for entry into operation in the next couple of years, and has already started further developments aimed at improving both launchers.

For satellites with masses well above 1,000 kg, VEGA-C (capacity 2,400 kg into 500 km SSO) should offer launches as primary payloads in coming years.

Satellites with a mass typically above 300 kg and up to 1,000 kg deliver critical European missions and generally have high, specific demands in terms of launch dates and orbital injection accuracy. However, they cannot expect to be primary payloads of medium and heavy launchers of much higher capacity at affordable cost and must therefore be considered as a launch market segment that requires special attention in Europe.

Europe has indeed extensively used the old Dnepr and Rockot launchers for launching a number of ESA and Copernicus satellites in the mass range 300 to 1,200 kg as primary payloads<sup>9</sup>, until both launchers ceased to be available, a few years ago.

Since then, Europe has been facing a critical lack of competitive services for the launch of individual or equivalent satellites in this mass range as primary payloads. These include high performance imagery satellites for European purpose or export market (in

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8 An organised constellation is composed of small satellites distributed across several pre-determined, generally equidistant, orbit planes.

9 "Launch as Primary payload" means launch with a specific launch date and accurate injection into a specific operational orbit.

single or dual launch), groups of micro-satellites in the 100 kg class forming one orbital plane of a small Earth observation constellation and very high performance institutional and commercial satellites whose mass goes up to 700 or even 800 kg.

#### 4.4.2 Range of small launchers to consider for Europe

*In view of this critical gap left in the European launcher family, of the relationship between launcher capacity and the accessible European launch market for small satellites, and of the need to maximise the scope of the accessible European and world market for cost efficiency purposes, payloads with a mass of 300 kg to 800 kg or 1,000 kg should be the preferred target for a small European launcher.*

*A launcher with a capacity of 800 to 1,000 kg is recommended as it would have access to a European market of around 5t per year, including full equivalent satellites of all planned small satellite constellations and some individual satellites above 500 kg, and to an open world market of up to 9t per year (including Europe) and even up to around 10t per year if one considers non-European satellites of mass exceeding 500kg, compared to around 3t per year and around 6t per year for a launcher capacity of 500 kg. Under these assumptions, a rate of around 8-10 launches per year could be achieved with this capacity.*

*For the sake of competitiveness, the targeted launch system should be flexible enough to support a variety of missions and services required from the world market, including:*

- the launch of one or several mini-satellites in the mass range 300 to 800 or 1,000 kg to Low Earth Orbit, as a primary payload, for the purpose of a dedicated mission or for populating one orbit plane of a small constellation;*
- the combined launch of such a primary payload with a secondary payload or the piggyback launch of micro-satellites or a cluster of nanosatellites with no specific orbit requirements, within the remaining capacity;*
- rideshare dedicated launches for large clusters of nano and micro-satellites having no specific orbit requirements, for a total mass up to 800 kg to 1 ton, which is considered as a form of optimum, by aggregators like Exolaunch.*

*A sensitivity analysis was performed to compare the average cost of launching all European satellites in the 300-500kg mass range as primary payloads for launcher capacities in the 500-1,000kg mass range. The scenario assumes also launching a secondary payload of 150 to 300kg or a cluster of smaller satellites after orbital manoeuvre and/or nano satellites in piggyback whenever possible within the remaining launcher capacity.*

*Considering the European market only, this sensitivity analysis suggests that the average cost of launching all satellites in the 300-500kg mass range as primary payloads would not be higher with a launcher in the 800-1,000 kg capacity range than a 500kg capacity. This is because the lower cost per launched kilogramme achievable with a higher launcher capacity compensates the higher number of launches required with a less favourable filling ratio, with a cost penalty starting to appear only around 1,000 kg.*

*The assumed launcher cost models include amortisation of development costs and recurrent costs, both increasing linearly with launcher capacity.*

*Under these assumptions, a launcher capacity of 800-1,000 kg would not be less attractive to Europe for launching satellites between 300 and 500 kg than a capacity of 500 kg, whilst offering a missing efficient launch solution for satellites in the 500-900 kg mass range and a more suitable capacity for rideshare dedicated launches.*

*Developments of micro launchers of 150 kg class capacity may be of interest for several reasons like pathfinding new technologies, innovation, attraction of talents, but could only capture a small fraction of the accessible launch market. This makes the operational sustainability of this class of launchers questionable in Europe.*

## 4.5 Recommendations for answering needs and market

### ► **Recommendation No.1:**

*From a need and accessible market perspective, Europe should focus on a capacity of 800-1,000 kg for a small launcher enhancing the family of Ariane and Vega launchers, capable of launching satellites over 300 kg as single or primary payload and/or smaller satellites as secondary payload or piggyback or in clusters in dedicated rideshare launches.*

### ► **Recommendation No.2:**

*Evolving launch requirements for new European security and defence space missions should be monitored, and the current forecast for small satellite launches should be reassessed in the middle of the decade, to narrow down the inherent uncertainties of the ongoing transition to the New Space era.*



## 5 SUMMARY OF LAUNCHERS AND LAUNCH SITES OPERATIONAL AND IN DEVELOPMENT

*The observed and predicted significant growth of the small satellite has triggered the emergence of new launcher initiatives aimed at offering the best technical and financial conditions compatible with that market.*

*In many cases, the initiatives came from private start-ups, financially supported by Venture Capital, in particular in the US; in other cases or in addition, by agencies, governments or larger companies involved in the development phase or committed as an anchor customer of the targeted launch service.*

*To the best of our knowledge, as of June 2021, around 100 new launchers have been proposed for small satellites, most of them undergoing their development phase, and more than 20 new launch sites.*

*The initiatives are based on a variety of concepts and technologies, with most of them adopting innovative industrialisation processes, in particular additive manufacturing.*

*Another 20 launcher initiatives have been identified, but not further considered, due to their much lower financial credibility and questionable ability to complete their development phase.*

*This is in addition to 40 existing launchers and 29 launch sites that are already operational and could address the same above-mentioned market segment.*

*The gross payload mass, including adapters and dispensers launchers can place on an SSO 500 km orbit, is used as the main launcher reference parameter.*

*When available, the User's Manual was the main data source for technical matters. Concerning financial data, and prices in particular, only public information sources were used (press/internet/conferences/publications). All the retained launchers are shown in Annex 7 (database of launchers).*

## 5.1 Existing launchers and launch statistics since 2016

Of all the launches that take place yearly, we have selected only those aiming to place satellites into LEO orbits. Table 1 (pages 40-41) shows the launchers and their yearly number used for that purpose since 2016.

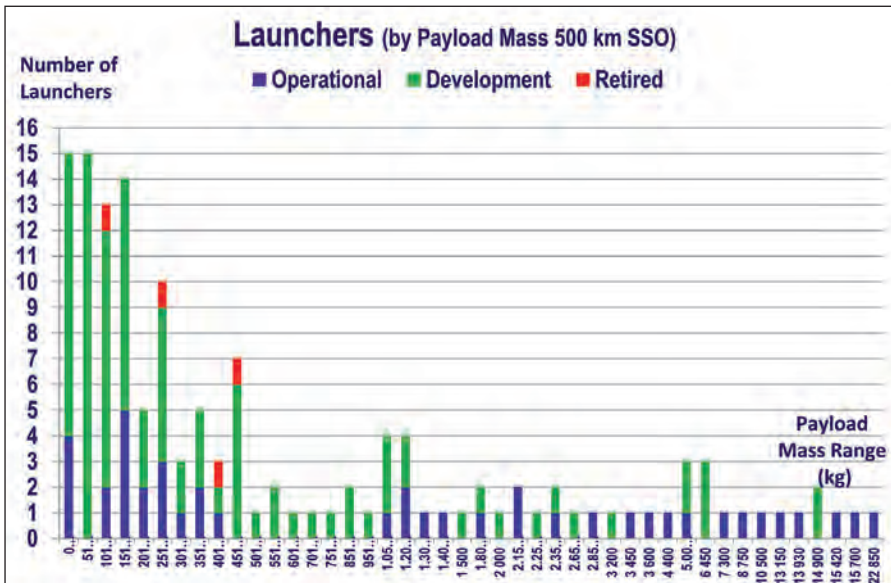
It is to be noted that out of the total of 532 launches during that period, more than half (334) were devoted to LEO orbits, with the US (110), China (105), and Russia (71) as the main actors. In the second range appear India (15), Japan (15) and Europe (11), while the remainder (7) are distributed among Iran, Israel and North Korea.

Two specific launchers, Falcon 9 and Soyuz, have cumulated the highest launch figures, largely separated from the others. Both launchers contribute with a similar amount (more than 60 launches each).

## 5.2 Assessment of existing and planned launchers by gross payload mass and price

The next two charts present a summary of all the analysed launchers, indicating first the development status and second, the identified specific price as a function of the payload range.

Figure 5-1 shows that the operational launchers are concentrated in the lower end of the payload mass range below 400kg, and are then more spread within the medium and heavy mass range.





Country	Launcher	2016	2017	2018	2019	2020	2021 Q1
China	Hyperbola 1				1		1
	Kuaizhou 1A		1	1	5	3	
	Kuaizhou 11					1	
	Zhuque 1			1			
	OS-M				1		
	Jie Long 1				1		
	Ceres 1					1	
	Kailuozhe 2A		1				
	Long March 2C		3	6	1	3	
	Long March 2D	6	3	8	1	7	
	Long March 2F	2				1	
	Long March 3B					1	
	Long March 4B	2	1	2	4	5	
	Long March 4C	2	1	3	3		4
	Long March 5B					2	
Long March 6		1		1	1		
Long March 7	1	1					
Long March 8						1	
Long March 11	1		3	3	3		
Falcon 9	3	11	10	8	21	9	
Electron		1	3	6	7	2	
USA							

Table 1: Number of yearly launches since 2016.

USA	Antares	1	1	2	2	2	2	1
	Pegasus	1			1			
	Minotaur		2				1	
	Launcher One						1	1
	Astra Rocket 3						2	
	Delta 2		1	1				
	Delta 4	1		1	1			
	Atlas 5	2	2		1	1		
	Soyuz	11	11	13	13	11		5
	Rocket	2	1	2	2			
India	PSLV	3	2	3	5	1	1	
Europe	Vega	2	3	2	2	2		
	Epsilon				1	1		
Japan	H-2	2	2	4	1	2		
	SS-520		1	1				
Iran	Safir				1			
	Safir 2 (Simorgh)				1	1		
	Qased						1	
Israel	Shavit 2	1					1	
North Korea	Unha 3	1						
Total LEO Launches		44	50	67	66	83	24	
Total Overall Launches		85	90	114	102	114	27	

*The absence of operational launchers in the range 451 kg - 1,050 kg is noteworthy, showing that there is currently no launch service on offer in the launcher capacity range. Out of the 94 launchers still under development, 36 (40%) have a full payload mass capacity below 150kg, where the market is expected to be relatively narrow, and 66 (72%) below 500kg. Only very few launchers appear with a capacity exceeding 1,300 kg.*

*Looking at how this industry has developed in the different countries we find that:*

- In China, the government decided in 2014 to treat civil space development as a key area of innovation and issued a policy directive to enable large private investment in companies interested in participating in the space business. The main players were two state-owned enterprises: the China Aerospace Science and Industry Corporation Limited (CASIC) and the China Aerospace Science and Technology Corporation (CASC). These new commercial launch companies received restricted technologies from military or public entities. Since then, according to the IDA<sup>10</sup>, 21 new companies are active in the launch sector, with particular emphasis on small launchers. Sometimes it is difficult to distinguish companies that are truly private and those that are more or less state-owned ones. To mention some: Galactic Energy, i-Space, and Link Space.*
- In the US, two initiatives can be considered as essential: the NASA initiatives, firstly the Commercial Orbital Transportation Services (COTS) programme in 2006, challenging US private industry to develop cargo and eventually crew space transportation capabilities that could meet the needs of ISS. Secondly, the Venture Class Launch Services (VCLS) initiative in 2015, to foster commercial launch services dedicated to transporting smaller payloads into orbit, in particular to low-Earth orbits and to promote the continued development of the US commercial space transportation industry. The second initiative is the reason for having the world's largest small satellite market, with complementary institutional and private components.*
- In Europe most of the initiatives started as private ones but soon gained support from different institutional bodies like ESA, European Commission, national entities, etc., though with limited budgets. Table 2 (pages 44-45) shows the details of current European launcher development programmes.*

*The United Kingdom can be considered a singular case in Europe, with as many as six companies trying to develop small launchers, whereas the country abandoned launcher activities at the start of the ESA Ariane programme, in which it did not participate.*

*Figure 5-2 shows the specific launch price in \$/kg (2020) actually offered or announced for various launchers in each payload mass range of 50 kg. The figures were determined by dividing the commercial listed price for a full launch service by the mass of the launched payload or the maximum capacity of the launcher.*

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<sup>10</sup> "Evaluation of China's Commercial Space Sector", September 2019, IDA Institute for Defense Analyses, document D-10873. IDA is a US, federally funded research and development centre.

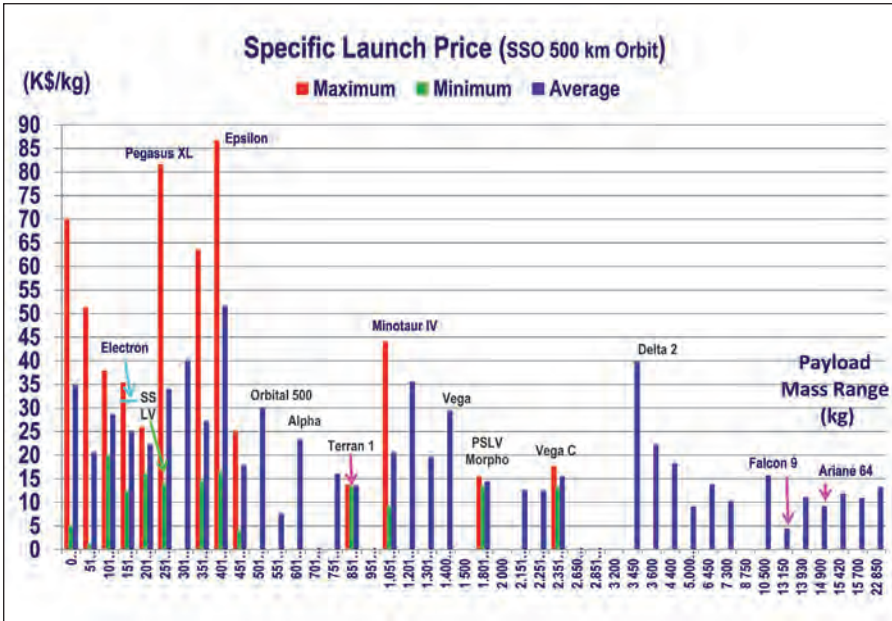


Figure 5-2: Specific launch price in k\$/kg (2020).

Whenever possible, three specific price values were retained for each payload mass range, i.e. the maximum (red), minimum (green) and average (blue) price. When only one specific price value is known, it is shown in blue, like an average value. The most relevant launchers are identified in relation to their specific launch price.

We realise that the data spread is very large, although a clear trend can be identified: price per kg decreases as launcher capacity increases.

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)	Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
EU	Avio	Vega Light	Dev.			300	11.8	39.2	Private/Public (ESA)	3 stages (solid) First: Z40 SRM (1.304 KN) Second: Z9 SRM (317 KN) Third: Z2 SRM (new)	55	2	Kourou (French Guiana)
EU	Avio	Vega	Oper.	2012	17 (2)	1 435	42	29.3	Private/Public (ESA)	4 stages (3 solid+1 Hydrazine/N2O4) First: P80 (3.040 KN) Second: Zefiro 33 (1.200 KN) Third: Zefiro 9 (213 KN) Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	137	3	Kourou (French Guiana)
EU	Avio	Vega C	Dev.	2021		2 390	42	17.6	Private/Public (ESA)	4 stages (3 solid+1 N2O4/Hydrazine) First: P120 C (4.323 KN) Second: Zefiro 40 (1.304 KN) Third: Zefiro 9 (317 KN) Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	210	3.3	Kourou (French Guiana)
EU	Avio	Vega E	Dev.	2024		2 700			Private/Public (ESA)	3 stages (2 solid+1 LOx/Methane) First: P120 C (4.323 KN) Second: Zefiro 40 (1.304 KN) Third: M10 (LOx/Methane) (98 KN)			Kourou (French Guiana)
EU	Ariane Group	Ariane 62	Dev.	2021		6 450	88.2	13.7	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	530	5.4	Kourou (French Guiana)
EU	Ariane Group	Ariane 64	Dev.	2021		14 900	135.3	9.1	Private/Public (ESA)	2 stages (LOx/LH2) + 4 solid boosters	860	5.4	Kourou (French Guiana)
EU	Ariane Group	Ariane 5	Oper.	1996	109 (5)	15 700	170	10.8	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	780	5.4	Kourou (French Guiana)
France	Venture Orbital Systems	Zéphir	Dev.	2023		70			0.9 Private Public (ESA, CNES)	2 stages (LOx/RP1) First: 6 engines Navier Second: 1 engine Navier		1	
France	ONERA	Altair	Dev.			162.8	5	30.7	Private Public (ONERA, CNES)	EOLE Aircraft + 2 stage rocket (Hybrid) First: 7 engines (HTPB/H2O2) Second: 1 engines (HTPB/H2O2)	15	1.2	Kourou (French Guiana)
France	Hybrid Propulsion	Mk2	Dev.	2024		200	4	20.0		2 stages (LOx/solid fuel)	20	1.2	
France	ArianeWorks	Morpho Micro	Dev	2027		500	12	24.0		2 Stages (LOx/CH4) First reusable (3 Prometheus 2.940 KN) Second stage: Not yet defined			Kourou (French Guiana)
France	ArianeWorks	Morpho Mini	Dev			1 800	24	13.3		2 Stages (LOx/CH4) First (7 Prometheus 6.680 KN) Second stage: Not yet defined			Kourou (French Guiana)
Germany	Hym impulse	SL1	Dev.	2023		400	7.8	19.5	3 Private 11 (Public?)	3 stages (LOx/Paraffin) First: 8 HyP/LOx25 (648 KN) Second: 4 HyP/LOx25 (400 KN vac) Third: 4 HyP/LOx25 (110 KN)	36	2.2	SSC Esrange (Sweden) North Sea Mobile Platform? Kourou (French Guiana)?

Table 2: European launcher development programmes.

Germany	Isar Aerospace	Spectrum	Dev.	2022		756	12	15.9	110 (Private)	2 (LOx/Light Hydrocarbon) First: 9 Aquila engines (675 kN) Second: 1 Aquila engine (94 kN vac)	65	1.8-2.5	North Sea Platform Kourou (French Guiana)?
Germany	Rocket Factory	RFAOne	Dev.	2022		1 275			17.5 Private (OHB: 46.4 %)	3 stages (LOx/RP1) First: 8 ORSC engines (<800kN) Second: 1 ORSC engine (100 kN vac) Kickstage: 1 engine (1.5 kN vac) (?)	2.1		Andoya (Norway) Kourou (French Guiana)?
Italy	Siderous Space Dynamics	EOS	Dev.			10	0.105	10.5		SSTO (H2O2/Butane) 40 kN Reusable	2.07		
Norway	NAMMO	ENVOL	Dev.	2024		218	6.4	29.5	Private	3 stages (Hybrid: H2O2/HTPB) First: 6 modules (630 kN) Second: 1 module (114 kN) Third: H2O2/RP-1 (6 kN)	34	1.5	Andoya (Norway)
Spain	Celestia Aerospace	Space Arrow CM	Dev.			16	0.2	12.5	Yes (Private)	Air launch + 3 stages (solid?)			MIG29-UB Air-launch
Spain	Zero2infinity	Bloostar	Dev.			78	4	51.3	13.83 (Private)	Balloon (30 km) 3 stages rocket (LOx/Methane) Reusable	4.9	2.9	El Arenosillo (Spain)
Spain	Pangea Aerospace	MESO	Dev.			120	4.54	37.8	1.1 Private (The crowd angels)	2 stages (liquid) aerospike engines: 30 - 300 kN First stage recovery			
Spain	PLD Space	Mitura 5	Dev.	2024		450	8	26.7	32 (GMV, Caixa Bank) (CDTI, JME Ventures)	2 stages (LOx/RP1) First: 5 Tepral C (408 kN) Second: 1 Tepral C (65 kN vac) Kick stage: Optional First stage recovery (parachute)	32	1.8	Kourou (French Guiana)
Sweden	Swedish Space Co	Rainbow	Dev.	2021		150							Kiruna (Sweden) North Sea Middle Platform? Kourou (French Guiana)?
UK	Smallpark Space Syst.	Frost 1	Dev.	2023		100	1.3	13.0	0.15				
UK	Space Launch Services	Pro-methus-1	Dev.			100				3 stages (H2O2/RP1)			Andoya (Norway)
UK	Orbex Space	Prime	Dev.	2022		150			39.8 Private (Delmos, UK Space Agency) (Sunstone&Gründerf. Vert Cap) ESA: 7.45 M€ (2021)	2 stages (LOx/Propane) First: 6 engines (xxx kN) Second: 1 engine (yy kN vac) First stage recovery	18	1.3	Sutherland Spaceport (Scotland)
UK	Black Arrow	Black Arrow 2	Dev.			300	6.3	21.0	0.1	2 stages (LOx/LNG) First: 5 engines (450 kN) Second: 1 engine (90 kN vac)		1.8	Seaborne launch vessel
UK	Skyrora	Skyrora-XL	Dev.	2023		315	12.6	40.0	4.85 (Private)	3 stages (H2O2/RP1)	56	2.2	Sutherland (Scotland)
UK	Orbital Access	Orbital 500	Dev.	2023		518	15.5	29.9	0.2 (Private)	Air-launch (MD-11): H=13,000 m First: Reusable spaceplane (H=80 km) Second stage: expendable			Prestwick (Scotland)

### 5.3 Types of launch services offered for small satellites

The types of launch services currently offered or planned for small satellites are summarised in the following table. Their prices are still very uncertain, as is the future availability of adequate piggyback launch opportunities on medium or heavy launchers.

<b>Types of launch services</b>	<b>References<sup>11</sup></b>
<p><b>Launch as primary payload.</b> Direct injection into operational orbit. Choice of the launch date.</p>	<p>Small launchers (Electron, Launcher One, Firefly): \$23K/kg to \$40K/kg.</p>
<p><b>Launch as secondary payload</b> (without priority on launch date) with a kick stage providing the necessary (potentially large) orbital transfer to operational orbit. Injection delayed by few days for altitude or inclination change and up to 2 months for RAAN change of 30°.</p>	<p>Small launchers: \$23K/kg to \$40K/kg.</p>
<p><b>Launch in piggyback</b> on a transfer module providing the necessary (potentially large) orbital manoeuvres (low thrust, high <math>I_{sp}</math> orbital transfer module). Injection delayed by few weeks for altitude or inclination change and up to 3 months for RAAN change of 30°.</p>	<p>Falcon 9 + transfer module with large capacity (e.g. Vigoride planned by Momentus). Overall launch cost &gt; \$15K/kg.</p>
<p><b>Launch in piggyback</b> on a transfer module for orbital positioning (orbital transfer module with chemical propulsion). Orbit almost imposed by the piggyback launch.</p>	<p>Launch in piggyback + transfer module with limited capacity (ex. SL-OMV from MOOG).</p>
<p><b>Launch in piggyback or clusters.</b> Orbit imposed by the launcher.</p>	<p>Falcon 9 \$5K/kg for packages of mass &gt; 200 kg (launch with Starlink SSO spacecraft). PSLV \$30K/kg (1 kg payload).</p>

Table 3: Small satellites launch services.

<sup>11</sup> Publicly available information or announcements.

## 5.4 Recommendations for European projects

### ► **Recommendation No.3:**

*Some European countries may wish to rely on a large offer of launch services in the world, others may prefer a European non-dependent launch solution dedicated to small satellites. The latter countries should identify and consolidate their civil and defence institutional needs and resources to ensure the success of at least one satisfying solution.*

### ► **Recommendation No.4:**

*Space agencies should, through a yearly “European small launcher working group conference” gathering together the ecosystem of small launcher companies, large launch system providers, launch operators, investors, brokers, agencies and customers, facilitate the sharing of any information adding value to the overall European launcher ecosystem and its contributors, including:*

- *what each actor is doing and in which areas they are ready to cooperate,*
- *evolution of future institutional needs (civil and defence) as well as commercial market analysis.*

## 5.5 Existing and proposed launch centres

*Table 4 (pages 48-49) describes the existing or planned launch centres, as well as the launches that have taken place in those centres since 2016.*

*It is relevant to note that the number of planned new centres is similar to that of presently operating ones.*

*The many launch site projects in Europe present some opportunities but are also subject to limitations linked to safety, feasibility of some orbits and cost of access to the launch field.*



Country	Launch Centre	Status	2020	2019	2018	2017	2016
Australia	Arnhem Space Centre (N)	Proposed					
	Bowen Region	Proposed					
	Southern Launch (S)	Proposed					
Brazil	Alcantara Launch Centre (NE)	Proposed					
	Jiuquan Satellite Launching Centre (NE)		13	9	16	6	9
China	Taiyuan Satellite Launching Centre (N)		7	10	6	2	4
	Wengchan Satellite Launching Centre (SE)		5	1		2	2
	Xichang Satellite Launching Centre (Centre)		13	13	17	8	7
	Yellow Sea Platform (E)		1	1			
France	Guiana Space Centre		7	9	11	11	11
Germany	North Sea Mobile Platform	Proposed					
	Kulasekarapatnam (S)	Proposed					
India	Satish Dhawan Space Centre (Sriharikota) (S)		2	6	7	5	7
	Morotai island	Proposed					
Indonesia	Imam Khomeini Space Centre (N)		1	2			
	Quom Space Centre (N)		1				
Iran	Palmachim Airbase		1				1
	Tanegashima Space Centre		4	1	4	6	3
Japan	Uchinoura Space Centre	Small Launchers		1	2	1	1
	Mahia Peninsula	Rocket Lab L-Complex	7	6	3	1	
New Zealand	Andoya Space Centre (N)						
Norway	Sonmiani Satellite Launching Centre (S)						
Pakistan							

Table 4: Existing or planned launch centres and launches that have taken place since 2016.



## 5.6 Recommendations for European launch sites

► **Recommendation No.5:**

*The development of European launch sites will improve the competitiveness of European small launch service providers.*

► **Recommendation No.6:**

*The modernisation of the Guiana Space Centre should include development of the capacity for small launchers and stage recovery, review of safety rules and means and reduction of operating costs. Improvement of the range availability for a significant increase of industrial and launch co-activities should be taken into account as well.*

► **Recommendation No.7:**

*The space agencies should be active in developing and providing information on the criteria and conditions for new European launch sites to become efficient complements to the Guiana Space Centre. They should promote and organise the exchange of information between actors, including investors.*

► **Recommendation No.8:**

*In view of their substantial impact on launcher design and launch sites, flight safety rules have to be rethought within Europe and in coherency with the rest of the world.*

## 6 ARCHITECTURES AND TECHNOLOGIES

### 6.1 General principles of architectures

*The architecture of launchers is determined by a number of fundamental design parameters, among them:*

- *launch mode (e.g. vertical, horizontal, air launched);*
- *landing mode (if any);*
- *number of main stages, kick-stage and boosters;*
- *number and types of engines per stage, including fuel type;*
- *level of re-usability;*
- *level of autonomy;*
- *safety requirements.*

*Any launch vehicle developer has to make major design decisive options with regard to these parameters in the initial phase of the design, based on market requirements and their business case.*

#### 6.1.1 Air launched systems

*Since the 1990s, the need for small payload launches in LEO has led to the emergence of several concepts different to the traditional vertical launch, in particular the airborne type of launch, which has long been in operational activity (Northrop Grumman's Pegasus launcher).*

*Based on a three-stage, 23 t solid rocket (based on a former missile) for a payload of 440 kg and a cost of \$40 million, it requires a specific airborne platform (Lockheed L1011) with high maintenance costs that push up the overall cost. The rocket is dropped at 850 km/h at an altitude of 12,000m.*

*It can be noted that this concept avoids introducing boosters for this phase, given that the solid propulsion based on 90's technologies makes it difficult to reach a good structural coefficient (dry mass ratio); but there are other advantages:*

- *easier selection of drop zones for the launch vehicle by selecting the launch azimuth;*
- *relaxation of weather constraints;*
- *higher  $I_{sp}$  for the first stage nozzles compliant with the lower external static pressure on ignition;*
- *aircraft-like operation, no dedicated launch pad required.*

*The major drawback for air-launched systems comes from aeronautic safety rules: traffic management, stage fall down, landing with the launcher in the event of an aborted launch, which have consequences for design and performance.*

*The Virgin Galactic programme, which is much more daring in terms of technology (hybrid propulsion) and whose primary purpose is space tourism (max. altitude 100 km), was initially conceived as a low-orbit launcher with the potential for reuse of part of the vehicle. Difficulties encountered in the development of the hybrid propulsion system are causing considerable delays. For the record, they received a contract from OneWeb for a few launches, at \$5M per launch, but the contract was cancelled.*

*As a consequence, the Virgin Group (through another specific purpose company, Virgin Orbit) has developed a launcher that is airlifted by a Boeing 747 from the Virgin fleet, known as 'Launcher One'. This two-stage, 30-ton launcher uses LOx-RP1 propulsion. After an initial failure due to ignition problems on the first stage, it successfully completed its second flight test on 17<sup>th</sup> January 2021, carrying 10 NASA micro-satellites. The announced performance is 300 kg at 500 km SSO for a price of \$12M. The system had its first operational flight in June 2021.*

*From 2012 to 2016, there was also a project by a Swiss company: S3 (Swiss Space System), with a mini shuttle on the back of an Airbus A300. The shuttle was to make manned flights or to drop satellites and return to Earth. The project did not pass the first maturity gates and has been abandoned.*

*Some projects also propose air-launched systems from high altitude balloons.*

*All experiences show that air-launched systems are an option only for small launchers.*

### **6.1.2 Horizontal landing**

*Among possible and envisaged architectures, there is also the vertical launch-horizontal landing technology for re-entry from orbit. It has been validated by projects like the X37 (A and B, successfully flown several times) and the ESA Space Rider project. They correspond to a highly specific mission, since the primary goal is not related to launch small satellites. The hot re-entry function complicates the design and penalises the vehicle's mass, even more so for smaller launchers:*

- *lifetime in orbit remains limited (energy management), except if there is a solar array deployed in orbit or fuel cells (X37, Space Rider, Dream Chaser);*

- *the launch nevertheless requires a medium launcher of the >1500 kg SSO class: VEGA-C minimum but with limitations on latitude of the return site, due to launcher performances.*

### 6.1.3 Vertically launched systems

*In view of the experience acquired in recent years and the various existing rockets (Falcon, Electron...), the principle of an architecture based on "Two Stages To Orbit" (TSTO) probably best meets the goals of simplicity and therefore competitiveness. From a performance point of view (i.e., max. payload), three stages would be better (mainly dependent on the structural indices, the required total Delta-V and the  $I_{sp}$  of each stage). From a mission complexity and reliability point of view, each stage creates an additional risk regarding stage separation and ignition of the new stage, which reduces reliability. De-orbitation of the second stage needs dedicated avionics. From this point of view, lower stage numbers are preferable, with injection accuracy depending on the characteristics of the second stage engine. For specific missions, an optional additional stage (or kick-stage) may be required to increase the launch domain and the orbit accuracy.*

*From the industrialisation point of view, minimum cost will favour concepts with a smaller number of stages even if this calls for an attractive structural index. A good commonality of technologies in all stages, whatever their number, can be implemented in order to lower the production costs.*

### 6.1.4 Reusability

*Vertical launch architecture can take into account the ability to reuse the first stage, which usually represents more than half the cost of a launcher. The efficiency is linked with the chosen recovery concept and depends on the refurbishment costs. For example, the toss-back concept (validated on Falcon 9) requires a throttle engine (for a very low thrust at landing), an additional guidance system (IMU, computer, software, grids), additional fuel and recovery infrastructure. It significantly reduces the available on-orbit performance. However, refurbishment for toss-back concepts is cheap. Conversely, recovery concepts based on parachute descent and splashdown have limited impact on stage complexity and performance, but could generate more expensive refurbishment (under test by RocketLab). Parachute descent and recovery by helicopter is another concept under study.*

*One advantage of first stage recovery is the opportunity to offer two types of mission:*

- *a high energy mission with maximum payload without recovery;*
- *a mission with first stage recovery, more economical but with reduced payload capacity.*

*Analyses of first stage reuse have been done in Europe. They confirmed the complexity of the approach given all the different factors: lower production rate, increased fixed costs, refurbishment costs, need for mission flexibility depending on their variety, loss of performance, complex logistics.*

*The cost of reusability (especially if toss-back or winged) would be higher in percentage terms for a small launcher. Testing new concepts of reusability on small launchers would mainly be of interest to validate some technologies before transfer to bigger launchers.*

### **6.1.5 Kick-stage**

*Depending on the mission need, a 2-stage launcher could optionally be completed with a “vernier” thruster or kick stage. This would not actually be a third stage because it would not significantly contribute to increasing velocity but would rather perform payload spacing and improve in-orbit injection accuracy in the case of more complex missions when manoeuvring capacities of the second stage are insufficient.*

### **6.1.6 Regulations and operations**

*In order to comply with the applicable space debris mitigation rules, all these components for new launchers must have their own deorbit capability (international guidelines from IADC, ISO, UN-COPUOS, for instance, and national laws like the French space operations law).*

*Flight control safety, and more particularly “safeguard” aspects, will need to take into account the potential diversity of launch pad positioning and rely on a “Flight termination system”, thus dispensing with the need for heavy ground infrastructures such as radar and tracking stations, the reliability of which impacts launch system availability and costs.*

*In operations, the diversity of services to be provided (payload configuration and orbits) will create many specific activities in terms of mission analysis, including safety analysis and associated software development and validation, which would almost be specific to each launch. The consequences on cost and time to launch will have to be properly considered.*

*From the launch range aspect, it is simpler to launch a 20 metric ton class launch vehicle than an 80 ton class launch vehicle. In particular, it is important for the launcher design to maintain the possibility of launches from various pads and sites. Launcher to launch pad interfaces should be based on simple means (mechanical and electrical ground support equipment). While solid propulsion appears simpler to use than liquid propulsion, in particular with regard to cryogenic constraints, it nevertheless requires heavier infrastructures and handling means and greater safety areas, as thrusters must be handled in a loaded state.*

*Finally, the level of reliability delivered by the launch system must be high enough to ensure limited failures for the very high launch rate targeted by some projects.*

## **6.2 Innovative technologies contributing to technical and economic performance**

*The quality, performance and efficiency of any new launch vehicle are directly linked to a number of functions which rely on critical technologies. The more advanced these*

*technologies, the better the launch vehicle in terms of the mentioned criteria. The technology domains below at least have to be considered:*

### **6.2.1 Structures**

*A trade-off must be performed in the early stage of launcher design between carbon-fibre type composites and optimised metallic structure, not only in terms of performance and production cost but also industrial policy. The introduction of carbon-fibre type composites is certainly an interesting option, mainly for large structures including tanks, to reduce the structural mass index and increase stiffness. In this case, the design must be composite-oriented from the start of the project, not a transposition of metallic structure conception. Confidence in the supply chain in particular, mainly for long lead items and quality process management, is crucial and has an impact on margin policy and a fortiori on the structural mass index. This trade-off might vary between a smaller or larger launcher.*

*Automation tools and processes (fibre placement) offer an improvement on quality and production cost. The introduction of thermoplastic composites would certainly open up new avenues for optimising design and operability processes (damage tolerance).*

### **6.2.2 First stage reuse**

*Concerning the first stage in particular, components used for the ascent function must be reused for the return function (propulsion-braking, attitude control, actuators, sensors, etc.). Only aerodynamic and landing stabilisation elements (such as grids and stabilisers) might be specific to the return function but could be removed for a higher energy mission not requiring first stage reuse. Before copying existing solutions, an in-depth analysis of all requirements and goals must be performed and a stepwise risk mitigation approach is recommended. The recovery mode may have an impact on the choice of propulsion: toss-back for instance requires highly variable and re-ignitable main engines, which leads to a bi-liquid version (note that a hybrid version could be an option, but its TRL/IRL level is currently too low).*

*It can be noted that reuse of the fairing has been successfully achieved on Falcon 9, and some companies (SpaceX for Starship, Relativity) present projects with full launcher reusability, although with no details as to the upper stage recovery system.*

### **6.2.3 Actuators and devices**

*The need for simplicity of integration procedures and potential recovery rules out pyrotechnic systems in favour of electric actuators which, in addition to ease of operation (and reuse), have the advantage of being easily controllable, do not require specific safety constraints during integration and generate lower shock level. The use of "off-the-shelf" equipment (valves, electronics...) will dispense with specific developments, allowing the choice of proven technologies. However, the high weight of electric batteries and harness has to be taken into account in the design trade-off.*



### 6.3 Propulsion

The launchers analysed are equipped with various types of propellants. Table 5 presents the types of propellants used for the launchers in the payload range 0-1500 kg.

Operational launchers use only three types of propellants: solid, LOx/RP1 and Hydrazine/N<sub>2</sub>O<sub>4</sub>.

Operational	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	501-550	551-600	601-650	701-750	751-800	851-900	951-1.000	1.051-1.100	1.201-1.250	1.301-1.350	1.400-1.450	1 500	
Solid	2		1	3	2	4		1	1									1				1	
LOx/RP1			1	1															1				
Hydrazine/N <sub>2</sub> O <sub>4</sub>	1			1			1												1	1			
LOx/LH <sub>2</sub>																							
LOx/Propylene	1																						
Not identified																							

Table 5: Types of propellants for operational launchers within the payload range 0-1,500 kg.

Launchers still in development stage use a larger variety of propellant configurations, although again the most frequent ones are the solid type and LOx/RP1.

Development	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	501-550	551-600	601-650	701-750	751-800	851-900	951-1.000	1.051-1.100	1.201-1.250	1.301-1.350	1.400-1.450	1 500	
Solid	2	1	2	4	1	2			1	1		1		1				1					1
LOx/RP1		2	1	3		2	1	1	1	1			1		1	1			1				
LOx/Methane	1	2		1		1				1						1		1					
Hydrazine/N <sub>2</sub> O <sub>4</sub>								1															
LOx/LH <sub>2</sub>																							
H <sub>2</sub> O <sub>2</sub> /RP1		3	1				1																
Hybrid	3	1			1														1				
LOx/Paraffin			1					1															
LOx/Propylene																							
H <sub>2</sub> O <sub>2</sub> /Butane	1																						
LOx/Propane			1																				
Not identified	4	6	5	1	2	1		1		4	1	1					1	1					

Table 6: Types of propellants for launchers under development within the payload range 150-1,500 kg.

*The choice of propulsion system is decisive, given cost and performance targets and potential reuse. It must be apprehended in its system environment: stage, implementation, mission profile. On the basis of available information and experiences, a first assessment of the different options is presented below, analysed through the filter of the above-mentioned goals. Some options seem good candidates and are consistent with a flexible, efficient small launcher.*

### **6.3.1 Solid propulsion**

*Solid propulsion is currently used for small launchers when the policy underpinning them is one of autonomous national access to space with affordable development and investment costs and when a defence technology base (missile technology) exists.*

*Launchers with solid propulsion typically:*

- *do not allow for reuse;*
- *offer structural coefficients and specific impulses little suited to a TSTO, probably leading to a three-stage system. Solid propulsion is also less adapted to the required mission flexibility, although offering simple, reliable operational implementation. The thrust law is a compromise for the flight domain envelope and cannot change (adaptation and control of maximum acceleration and dynamic mechanical loads). As a consequence orbit injection precision is very low if no liquid additional stage is implemented;*
- *require high investment costs unless they can be shared with other programmes (civil and/or military), which is only possible with limited launch rates. High launch rates require dedicated investments and infrastructure;*
- *produce nitric acid in the atmosphere which is harmful for the environment.*

*A pure solid option does not seem the best way forward for a European small launcher.*

### **6.3.2 Hybrid propulsion**

*The principle of having a combination of liquid and solid propellant components in the propulsion system is not new, but operational deployment seems difficult and limited (see difficulties met by SpaceShipTwo). However, new projects are appearing, most of them initiated by start-ups:*

- *Hylmpulse GmbH, offering a sounding rocket from which is derived a launcher (SL1) with a take-off mass of 23 tons, three stages, a bundle of hybrid engines (LOx/paraffin) with a unit thrust of 75 kN, pressurisation by turbopumps and LOx/ethanol gas generators, for a payload of 400 kg at 500 km SSO. The announced performance seems optimistic, and the principle is not compatible with reuse;*
- *HyPrSpace (Hybrid Propulsion for Space), which aims to launch a 190 kg payload for half the cost of the Rocket Lab;*
- *the Altair hybrid engine project, in cooperation between ONERA and the Norwegian company Nammo, which will be used for a sounding rocket.*

*Leaving aside the apparent attractiveness of hybrid propulsion, its implications at system level for the specific needs of a launcher must be taken into account:*

- *at the level of the structural coefficient:*
  - *the need to pressurise the liquid propellant calls for high pressure tanks (“Blow-down” technique) or an additional pressurisation system: pressure fed with high pressure tanks and a pressure regulator or turbopump with a gas generator. This requirement has direct consequences on the mass of the structures, thus increasing the complexity of the hybrid propulsion engine and bringing it closer to that of a liquid engine;*
  - *hybrid propulsion seems well adapted to sounding rockets with a few tens of seconds of flight and small propellant volumes;*
  - *the obligation to control the combustion surface in order to maintain an adapted thrust law and limit the combustion instabilities inherent to the concept imposes a bundle-type architecture (taken into account by HyImpulse but not mentioned by HyPrSpace), which leads to “snowball” effects at the level of the inert structural masses and explains the need for a three-stage system, which increases cost.*
- *In terms of flight control:*
  - *thrust vector control requires nozzle orientation. The hybrid engine concept is not compatible with a gimbal assembly and therefore requires the introduction of flexible nozzle for the gimbaling of the thrust since aerodynamic or RCS (Reaction Control System) types of attitude control are not very effective for a first stage;*
  - *the separation of the stages by means of simple and inexpensive devices requires a perfect mastery of the “combustion tail” which seems difficult due to the very principle of hybrid propulsion. The same difficulty may also appear for in-orbit injection precision with the 3<sup>rd</sup> stage.*
- *Flight loads (dynamic environment):*
  - *the very principle of combustion (passage of fuel from the solid to the liquid phase and combustion) generates combustion vibrations in a frequency range that may be harmful to the integrity of the payload. These phenomena need in-depth analysis to be mastered in terms of frequency range and level.*

*Although the principle may appear attractive in general, for the time being hybrid propulsion does not seem to be compliant with performance requirements (mainly  $I_{sp}$ , structural index) and TRL and IRL need improving. Complementary developments are needed to improve understanding and for implementation in launcher systems.*

### **6.3.3 Liquid propulsion**

*Most small launchers, whether operational or in development, use liquid propulsion systems in which typically a combination of two liquid fuels are injected into a combustion chamber, ignited and burnt.*

*Various European projects are under study and development: Prometheus, DLR Lumen, M10 for Vega E, RFA, ISAR, PLD. Programmes already in operation (Electron) have adopted liquid propulsion, but with variations in the choice of propulsion system and propellants.*

*The general principles of the architectures described above (TSTO with reuse of the first stage), backed up by the experience acquired (Falcon 9), show that the option based on the same engine for both stages – 5, 7 or 9 for the first stage, and a single one for the second stage with some specificity (ex: divergent nozzle) – is certainly the one that offers the most possibilities. This modularity offers potential for further improvement while increasing the overall reliability of the first stage (engine failure already demonstrated by Falcon 9) and providing options for the number of engines to be reignited for the potential return function and thrust control.*

*These engines must be able to modulate thrust, be re-ignitable in flight and of course be reusable and compatible with an ergol optimisation system.*

*Even in the event of recovery of the first stage, this choice guarantees industrial continuity for the production of the propulsion systems of the two stages, for which the same pressurisation system will be sought.*

*Apart from very small launchers, the dimensions of these engines are limited by existing means of 3D printing, given that this 3D process contributes to optimising the design and therefore delivers a competitive weight/thrust ratio, attractive costs and reduced production cycles. It also allows for rapid design evolutions and optimisation thanks to return on experience. The need for cleaning the cooling system of the combustion chamber due to 3D printing definitely needs specific machining for surface roughness and residual powder removal.*

#### **6.3.3.1 Propellant management and attitude control**

*For all stages, an "Intelligent" propellant management function must be developed in order to limit unburned propellant (e.g. advanced sensors, flight exploitation), which has a direct impact on performance, including for the return function if this option is chosen. The mass of the unburnt fuel in the upper stage is directly equal to the loss in payload mass.*

#### **6.3.4 Introduction of green propellants for attitude control**

*The introduction of non-toxic propellants is consistent with the need for simplicity of use in a small launcher, by allowing launches from bases free of these constraints, hence the notion of "green propellants". These green propellants may be used to replace highly toxic propellant in the attitude control system of the launcher, mainly based on a pulsed mode with small thrust levels (10 to 150 N). The current systems are based today mainly on:*

- mono-propellant with catalytic bed decomposition with an  $I_{sp}$  in the range of 220-230 sec. Depending on certain configurations, a pressurised cold gas could meet the requirement (Nitrogen):*
- bi-propellant with hypergolic reaction (UDMH-N<sub>2</sub>O<sub>4</sub>) for higher thrust levels linked to the increase of velocity with an  $I_{sp}$  around 325 sec.*

*Leaving aside their very high energy characteristics (sensitivity to shocks), these products are extremely toxic and require constrained implementation conditions*

(anti-acid suits, pressurisation law, water hammer effect, etc.). These are often determining criteria in the definition of safeguard perimeters.

Green propellants do not eliminate the dangerousness of products, above all in energy terms (shock, thermal, corrosion, etc.). They avoid heavy constraints with regard to toxicity and carcinogenicity (use of a protective suit) but not those regarding safety.

- The adoption of “green propellants” is not limited to the propellants themselves, but requires the development of a complete system, possibly involving expensive technologies, e.g. a ceramic catalytic bed to withstand temperatures of 1,000°C, higher than hydrazine.
- System implications must also be integrated (preheating of engines to 250°C). In addition, the gases produced are highly charged with water vapour, resulting in interactions with payloads that must be analysed.
- Hydrogen peroxide ( $H_2O_2$ ) has already been used (Soyuz TM), but its performance is poor ( $I_{sp}=185$  sec), with difficulties of stability of the molecule over time.
- DNA-type technologies like the ECAPS LMP-103S single-engine option and the NASA AF-315E have been demonstrated in flight, but require further development to become a European solution. The level of specific impulse achieved would be acceptable for attitude control but insufficient for the creation of needed delta-V and they require pre-heating. The instabilities of the salts in the solvents must be subject of further development.
- The bi-propellant option with a hypergolic reaction would enable an interesting level of  $I_{sp}$  but still seems to be at a fairly low TRL level, i.e. it is a new system that needs to be developed. The oxidant used is hydrogen peroxide.
- A technology based on gelled propellants proposed by Bayern Chemie simplifies implementation and storage, but requires very high pressures for pressurisation, since it is the formation of spray that leads to the production of gas. Validations are needed in the environment of an operational system
- Given the information available and accessible in the open documentation, it seems that there is a gap between the announced performance ( $I_{sp} = 300$  sec) and the technological reality. The levels of both TRL and IRL are not sufficient to approach operational development in the short term. A higher TRL level is needed to judge this technology. The definition “green” is somewhat misleading. It is a question of toxicity, which that is why the wording “non-toxic” is preferable; action should be taken in coherence with the main propulsion with regard to environmental constraints.

### 6.3.5 Synthesis for propulsion system

The economic attractiveness of a “small” launcher also depends on optimising its performance. Only ambitious structural coefficients allow for a TSTO type concept. Otherwise, a three-stage version (or one with boosters) is required, thus increasing the cost. This optimisation is conditioned by maximum interpenetration between the propulsion system and the launch system.

*A TSTO architecture incorporating the same liquid propellant engine with 5 or 7 or 9 engines in the first stage and one in the second stage, based on 3D technology – is probably a good option.*

*LOx/LCH4 type propulsion offers the best potential for evolution, especially with regard to reuse and with respect to environmental constraints. It would be in line with investments already made in Europe to improve the TRL level (in coherence with the Ariane cryogenics legacy, and technology advances).*

*Regarding the Rocket Lab approach, an electrical turbopump may be also a great advantage for optimising propulsion performance of a small launcher and could be an asset at system level, subject to acceptability of the weight of the batteries.*

## 6.4 Manoeuvring systems

### 6.4.1 Introduction

*For multiple small satellites launch, specific devices (“dispensers” or “deployers”) are needed for interfacing with the launcher, separating and ejecting the satellites. Dispensers for nanosatellites, microsatellites and even mini-satellites are proposed for different types of launchers, by specialised companies acting as brokers<sup>12</sup> and/or payload integrators.*

*Worldwide, several broker companies are now extending the function of their dispensers to that of orbital transfer vehicles by adding subsystems, notably propulsion, power generation and avionics, in order to perform orbital manoeuvres after separation from the launcher and before delivering their payloads into operational orbits.*

*Spaceflight Industries for example has plans to develop different variants of its “Sherpa module” with different types of propulsion subsystems, ranging from chemical mono-propellant to electric ones. Exolaunch in Germany is developing its “Reliant” space tug. Several transfer modules with their payloads can be launched together in piggyback or rideshare on board medium or large launchers such as Vega, Ariane 6 or Falcon 9.*

*As an example, Exolaunch has already made reservations for their systems on board a Falcon 9 launch in 2021 into a Sun Synchronous Orbit.*

*The advantage of being able to perform multiple launches such as the launch of two subsets of payloads aiming at two different orbits is also recognised for small launchers. The size of the manoeuvres depends on the pairing of payloads and their different orbital requirements. Increasing the size of the manoeuvres also increases their duration and costs (additional masses to be launched, cost of the systems and cost of the operations).*

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<sup>12</sup> *Small Satellite Launch Brokers are companies that organise launches for small satellites by securing launch opportunities using one or different launch service companies and taking care of all the interfaces between the launcher and the small satellites under contract. They can organise dedicated rideshare launches for small satellites. Complementary to launch services they often offer mission management services and testing of small sats.*

*Due to the masses of transfer modules, the implementation of an orbital manoeuvre capability is likely to be quite different for small launchers than for medium or large ones.*

### 6.4.2 Types of manoeuvres

*Depending on whether or not the satellites themselves are equipped with a propulsion system with more or less velocity change ( $\Delta V$ ) capacity, the capabilities that should be sought for orbital transfers appear to be, in order of importance:*

- *the fine tuning of the relative (between satellites) or absolute position along the orbit, altitude and/or inclination. This fine tuning can be done better by the satellites themselves when they have their own propulsion system, even with limited velocity change capacity;*
- *a change of altitude by up to few hundred kilometres and of inclination by up to few degrees (especially in the case of SSO launches);*
- *a shift in the RAAN (right ascension of the ascending node, Mean Local Time in case of sun-synchronous orbits) by up to several tens of degrees.*

*This last capability goes hand in hand with the ability to change the orbit altitude (semi major axis) up to several hundred km or the inclination up to 5 or 10 degrees, depending on the range of the nominal orbit inclination (see Annex 6). This capability is intended, for example, to enable injection of satellites into different planes of a single (homogeneous) constellation.*

### 6.4.3 Orbital manoeuvres with transfer modules

*Orbital manoeuvres can be carried out by systems fully independent of the launchers themselves in cases of launches on board medium or large launchers.*

*The typical capabilities of the various modules already developed or in the final development phase in the world range from large to relatively small orbital transfer capability:*

- *large orbital transfer capability with electric propulsion system:*
  - *electric propulsion is able to deliver a high specific impulse ( $I_{sp}$ ) but for a given level of electric power, the lower the level of thrust the higher the  $I_{sp}$ . Therefore, the manoeuvre duration increases as the  $I_{sp}$  increases;*
  - *using electrostatic/ionic propulsion with specific impulse  $> 1,000$  sec for transfer modules is very efficient in terms of propellant mass but also very penalising in term of manoeuvre durations;*
  - *using electrothermal propulsion with an  $I_{sp}$  around 600 to 800 sec appears as a more favourable option for large manoeuvres. Electrothermal propulsion (e.g. Arcjet), with several kW of available power, has been used in the US on GEO telecom satellites, but the development of low power Arcjet propulsion systems, which could be convenient for transfer modules dedicated to small satellites, is still at a low TRL. However, Momentus (US) claims today that their proprietary microwave electrothermal propulsion technology (using water as propellant) is able to deliver*



*specific impulse of 700 sec. In Europe initiatives for development of electrothermal propulsion remain limited;*

- *small orbital transfer capability:*
  - *because chemical propulsion does not require electrical energy from solar generators, it is suitable for modules with low transfer capacity, especially for limited altitude change, more precise injection and for positioning multiple satellites along an orbit plane. MOOG, for example, use chemical propulsion for their Small Launch Orbital Manoeuvring Vehicle.*

#### **6.4.4 Orbital manoeuvres with an additional optional stage**

*A Two-Stage-To-Orbit (TSTO) configuration is probably the most competitive one for a small launcher. However, the diversity and flexibility of missions required from a small launcher to meet market demands might be incompatible with the manoeuvring capabilities offered by the second stage and its attitude and control system. The second stage of such a launcher would not be able, in most cases, to offer the orbital manoeuvre capability needed for secondary payloads (one or several satellites aiming at the same orbit different from the orbit of the primary payloads)<sup>13</sup>. Use of an Additional Optional Stage (AOS) could be useful for the following main reasons:*

- *For specific missions or customer requirements, the performances of the 2<sup>nd</sup> stage propulsion system (notably the MIB: Minimum Impulse Bit or Burst) might not reach the required accuracy.*
- *Launch of multiple payloads requires clean “drops” to ensure non-collision. It must be remembered that, as these are small launchers, upper part inertia is low and the slightest disturbance can be the source of parasitic movements that could disturb the jettisoning (collision risk). It is therefore necessary to compensate for any deviations caused by a change of the centre of mass of the sub-assembly. The sequence of spacecraft separation is also tricky for this reason.*
- *Delta-V capability of an AOS (typically up to 1,500-2,000 m/s) would provide significant flexibility for pairing payloads in view of multiple launches. Chemical propulsion with specific impulses of typically 300 sec and thrust level of several tens of Newtons would allow altitude or inclination change with relatively high propellant mass but with duration limited to few hours or days.*
- *The propulsive capacity of an AOS could also support the mission range by making up for the propulsive deficit of the lower stages, thus increasing reliability.*
- *Deorbiting is required by the French “Loi sur les Opérations Spatiales” (Space Operations Act). In the launcher configuration without AOS, the 2<sup>nd</sup> stage of the launcher would perform the necessary deorbit manoeuvre after satellite(s) separation.*

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<sup>13</sup> *The launch flexibility offered by Rocket Lab with Electron is based on a two stage plus kick stage configuration. The kick stage ensures orbital maneuvers with potentially multiple trajectory changes and deorbiting. The Rocket lab kick stage seems to use a chemical Curie engine for change of velocity and cold gases for attitude control, which is simpler for managing the MIB and does not require a complex system.*



*In the full configuration (with an AOS) the second stage trajectory could be limited to sub-orbits, resulting in a natural re-entry (consequences on the launch site and trajectories have to be analysed). The AOS would perform its own deorbiting after the end of the orbital manoeuvre and secondary payload injection.*

- *An additional mission could be assigned to the AOS before deorbiting, such as debris capture for orbit removal, obviously to the detriment of the payload capacity.*

*The launcher architecture could be designed in such a way that equipment and functionalities – guidance, navigation, attitude control, sequential and energy management... – could be shared between the TSTO function and the AOS. They could be integrated into a common bay, which could be attached to the TSTO, when no manoeuvring capability is required (lower configuration), or to the AOS for the “full” configuration. This is valid if the second stage remains sub-orbital for a non-controlled re-entry.*

*The loading of propellant inside the AOS could be adjusted according to the mission request (different size or number of tanks) in order to enlarge the mission domain in terms of performance and flexibility without any other change. Obviously, the higher the mass of the propellant in the AOS, the lower the mass offered to the payload.*

*We could target an AOS dry mass in the order of 200 kg to 300 kg respectively for launchers of capacities 500 kg to 1,000 kg. As an illustration, with a launcher of 800 kg capacity, it would be possible to launch two satellites of 300 kg each in two orbits with a difference of up to  $\sim 6^\circ$  in inclination (see details in Annex 6). To achieve this, a structural index in the order of 15% would be necessary.*

*It is widely recognised that, unlike the two nominal launcher stages, the AOS would have to be compatible with a lifetime in orbit of a few days in case of inclination or altitude manoeuvres and a few weeks when a large drift of the RAAN (Right Ascension of the Ascending Node) is required.*

#### **6.4.5 Synthesis for manoeuvring systems**

*When a large orbital manoeuvre capacity is requested, the use of independent orbital transfer modules results in significant additional mass to be launched. Typically, the additional mass can be up to two times the secondary payload mass. This is why the utilisation of such transfer modules on board medium and large launchers with low launch cost per kg may be attractive in spite of the additional costs for the modules themselves, while their use with launchers below 1,000 kg capacity is questionable.*

*With small launchers, large manoeuvring capability could preferably be provided by an Optional Additional Stage. When an AOS is used, specific adaptation of tank and propellant launch to the total mass of the payload and the manoeuvring requirements of the secondary payload should be made possible.*

### **6.5 Evolution of design and management rules**

*European design rules and the rigour associated with them enabled the Ariane programmes to achieve global standing. However, despite 220 Ariane 4 and 5 flights and all the lessons learned, the system seized up due to the industrial organisational*

*cascade and the piling up of successive margins and precautions, all along the supply chain. For instance, the cascade of margins is never reviewed in the contractual context which is frozen according to the qualified configuration.*

*These rules, which were and still are the reference for two generations of engineers, have changed little. It is important to understand why there are such discrepancies between SpaceX, which has 15 years of operational history, and Ariane, which has 40 years of history when the margin criteria are the same (e.g., qualification load = limit load x 1.25).*

*More agility and efficiency need to be generated in Europe. Several potential ways can be proposed:*

- a pragmatic approach to avoid the accumulation of margins, based on feedback from experience through better exploitation of flight data and the search for the best compromise between “system requirement” and “technologies potential improvement”;*
- more precision in the content of acceptance tests (or flight readiness tests) throughout the chain, right up to final integration, in order to eliminate all margins due to production and integration hazards and dispersion.*

*Margins are established at the beginning of a programme, due to uncertainties underlying the physics, the models’ representativeness and the industrial process. Exploitation of the first tests and several flights must be clearly oriented towards the reduction of margins. Two mandatory topics must be sustained:*

- alert from a non-expected event;*
- better environment knowledge to improve load requirements.*

*New sensor and transmitter technology is an asset in implementing cheap telemetry.*

*SpaceX has largely developed the “learning from tests” approach and it would be wise to introduce “demonstration” tests instead of the so-called “qualification” tests, to build or recalibrate calculation models with margins reduced to the strict minimum necessary to cover uncertainties and manufacturing dispersions. These uncertainties or dispersions have to be reduced during the operational life, allowing for either a cost gain or a performance gain. This means improving the European approach, in particular with regard to the famous and unchanging “qualified configuration”.*

*In order to ensure that the launcher is always optimised in terms of economic stakes and with regard to the competition, an improved quality process should be implemented, which could authorise changes in performance and processes based on a controlled incremental evolution and qualification. The same goes with respect to the industrial processes. New tools like digital mock-ups, 3D printing, etc. are assets that must be exploited.*

*It is indeed the European development approach to engineering (traditional V-shaped) that can be questioned because of its rigidity. Alternative approaches widely used e.g. by SpaceX, stem from software development methodologies (spiral method). Throughout the life of the programme, the quantification of the potential for evolution must be exploited, in order to transform it into an economic margin by a simplification of the*

processes or an improvement in performance according to the evolution of the competitive situation.

A small launcher programme, because of its scale, can be an excellent platform for experimenting these new approaches with a view to subsequent larger-scale development. The large-scale technology integrators currently involved (Themis demonstrator, Prometheus, etc.), because of their prototype nature, are not sufficient; it is necessary to integrate operational and industrial components (product recurrence); this could also be an objective for the development of a small launcher in which the innovation axis would be one of the drivers.

## 6.6 Recommendations for European small launcher concepts and technologies

### ► **Recommendation No.9:**

*Two-stage vertical launches should be favoured, with a staging adapted to the selected recovery/reuse mode and with orbit injection precision provided by thrust modulation (electrical turbopump or other devices). The launcher concept should be flexible/modular and allow for evolution over time.*

### ► **Recommendation No.10:**

*Technological development in propulsion (LOx-CH<sub>4</sub>, hybrid, "green" propellants), light structures (carbon or metallic) and recovery modes must be accelerated, including the use of real-scale demonstrators. Once validated for small launchers, such technologies may be adapted to medium and heavy launchers.*

### ► **Recommendation No.11:**

*There is an urgent need to review the design and qualification rules and practices used in Europe to achieve competitive launchers<sup>14</sup>.*

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<sup>14</sup> *Benchmarking with successful projects and feedback from European experience must be better exploited in domains such as: construction indices for engines and stages, especially the upper stage, load duration and levels statistical analysis, identification of margins to reduce test levels on payloads or launcher evolutions, calibration of thermal, structural, propulsion margins, minimisation of unknowns, acceptability of high-altitude winds, etc.*

**► Recommendation No.12:**

*The range of possible services offered by innovative kick-stages and orbital manoeuvrability devices should be investigated as they may be game changers for launch service operators. Such service capabilities should be developed for small launchers as well as for Ariane 6 and Vega C.*

**► Recommendation No.13:**

*Development of "green" or non-toxic propellants and development of electro-thermal propulsion technology (or equivalent from the performances point of view: specific impulse and thrust level for a given level of input power) should be pursued in Europe.*

## 7 COSTING AND FUNDING

*This chapter presents the most significant factors influencing the cost of small launchers and introduces some methods of funding non-recurring phases. It does not deal with the launching of small satellites by large launchers, whose characteristics are well known: in general, they need small non-recurring budgets to adapt to cluster launches (only the development of an adapter or orbital stage, as is the case with small launchers that also perform rideshares) and their recurring costs (RC) can be very competitive, less than \$10k/kg, but they present the disadvantage of not being able to offer a dedicated launch.*

### 7.1 Cost factors approach

*When designing, building and operating launchers, a great variety of factors drive their costs. It is not therefore possible to build a simple theoretical model providing a correlation between performance and costs. This section will provide a general overview of the large spectrum of drivers to be considered for cost efficient solutions.*

### 7.2 Non-recurring phase

#### 7.2.1 Launcher development and industrialisation

*A first key element impacting development costs is the experience of the development team (technological, technical, industrial, test campaign operations, launcher design...). Next in importance, in addition to an adequate system design, is the choice, availability and mastery of numerous technologies. Among these, propulsion is a key aspect for any launcher, along with system design and a very precise overall architecture. Any deficit in these key aspects could easily eat up the whole launcher performance since the payload represents only about 1 % of the total mass at lift-off.*

*Other items impacting costs are access to test facilities, complexity of operating industrial facilities, mastery of advanced production techniques, and quality control (in development and production). For a cost-effective exploitation phase, important aspects are the degree of production automation and ease of carrying out acceptance tests or inspections in the event of product anomalies. In general, digitisation of the product and the development environment has a strong influence on development costs. More generally what is called industrialisation has a major influence on the efficiency of the production system at large. Soon after the maiden flight, supposing it is successful, the challenge is to rapidly ramp up production rates, ensure a high degree of reproducibility and master product costs. So sufficient investment in a mature, flexible production and test infrastructure will pay off later, even if it is a higher upfront effort.*

*Development time, which is highly dependent on the above-mentioned choices and associated risks, is also an important cost factor. It is often underestimated for new developments. Examples include SpaceX's Falcon 9 (begun in 2002 for a first flight of F9 in 2010), Rocket Lab's Electron (begun in 2006 with a first launch in 2017) or Virgin Galactic's Launcher One (begun in 2004 for a successful first suborbital flight in 2019). All of them underestimated the difficulties and missed their initial development deadlines by several years.*

*The type of industrial organisation will also impact cost in both the development and operational phases. Latest examples of purely industrially driven setups seem to show that a 70 to 80 % vertical integration of all activities within one single industrialist leads to lower costs and better reactivity, since many contractual steps and boundaries disappear.*

## **7.2.2 Launch and recovery infrastructure development**

*The first question in this section is whether or not the future operator already has access to an available, properly equipped launch site with experienced personnel. If such an infrastructure has to be created, as many European countries are currently considering or even proposing at present, the first factor will be accessibility to the location by inexpensive means of transport. The success of such initiatives will be determined by the potential constraints associated with this factor, as well as the availability of experience in developing ground infrastructures, and the ability to mobilise competent actors and to find external funding for the infrastructure. Both direct costs (construction of the base, specific launcher facilities, payload preparation infrastructure, etc.) and indirect costs (maritime access routes, air and road transport, security and firefighting infrastructure, etc.) must be considered. One important aspect in terms of investment and regular maintenance is ground-based flight monitoring and telemetry means. Managing in-flight safeguard is another element that can vary greatly depending on the requirements and solutions imposed.*

### 7.2.3 *Design norms and standards, qualification/certification development process, Space Regulation requirements*

*This area probably has the greatest disparities and the greatest risk factors for new launcher development. Programmes under the authority of space agencies are generally compelled to apply rules, norms and standards that are the result of 60 years of experience. This contributes greatly to the reliability and robustness of the launcher, but at the cost of considerable effort and certainly to the detriment of performance optimisation. New players operating in an industrial, private framework can afford much simpler approaches. However, they must also ensure the safety of persons and goods at all times. The ability to judge the “lower” limits of standards and good practices to be imposed and therefore to master the risks of these simplifications with the goal of optimising (minimising) the cost/risk equation is one of the most demanding tasks for any recent company, often with limited background experience.*

*The effort dedicated to qualification or “certification” must meet customer expectations in terms of proven reliability, but also the legal requirements defined in what is called the LOS (“Lois des Operations Spatiales” – Law of Space operations) in France. The latter defines the justifications required by the State for its public risk-taking as a launching State for a given system.*

*However, it should be noted that many countries are considering launch operations without having regulations for the certification of launch objects and launchers, which may raise questions of liability as well as safety for the surrounding population and neighbouring states. In Europe, Germany, Sweden, Norway and Spain are supporting small launcher projects, but have not yet put in place a legal framework. The United Kingdom has recently adopted a first regulation of this type.*

*Development logics are often subject to strong budgetary and schedule constraints. Issues such as the extent of digital simulations versus testing, given that both approaches have their limits, have a significant impact on costs. At the test level, there are also many possible strategies between testing elementary components, sub-assemblies and full systems, but no test is fully representative of a flight, hence the frequent failures of the first flights of new players. Every time, access to existing resources and the number of tests in relation to the widest possible coverage of operating ranges will, on the one hand, secure knowledge and control of the product and, on the other, impact the corresponding expenditure. Given the differences in approach, comparisons are very difficult in this area.*

*It is clear that for small launchers, access to 3D printing technology allows the use of the “Design-Produce-Test-Fail-Redesign” method with costs and production cycles that appear competitive with regard to traditional methods and make access to space apparently easier. It is less applicable to large launchers, given the cost and time required to manufacture many prototypes.*



### 7.2.4 Innovation and new technologies

*In general, cost reduction factors identified by new players are to be found in design, technology choices and production methods. In the development phases, it is a question of mastering the performance and sizing methods linked to these new technologies as well as any industrial issues. Currently, most players are focusing on carbon structures, 3D printing and electrical systems for Thrust Vector Control and Turbopumps. 3D printing, which is a young and promising discipline for highly integrated products in fairly limited series and of small size, compatible with the current limits of printing machines, enables new design approaches but raises the question of final product quality and inspection. Used extensively for the engines of small launchers, it is necessary to determine from the outset how to inspect these complex and highly integrated parts at minimal cost.*

*It is important to adopt a global innovation vision for all phases of a system's life cycle. Leaving aside the temptation to focus on the launcher's most visible technology and performance, costs in the operational phase are largely dependent on the degree of industrialisation achieved or aimed for, on integration methods and strategies, on the ability to inspect and test the product and on the simplicity of operational procedures. Flexibility to react to and resolve unforeseen events will be important, in which a high level of digitalisation would seem to be a key factor.*

*It should be noted that all the most advanced small launcher projects aim for high production and launch rates, some even very high (in the order of 100 to 300 per year); this is a necessary assumption in order to try to reach the prices promised to the market.*

### 7.2.5 Non-recurring budgets

*Generally speaking, companies do not really communicate on their needs in terms of non-recurring budgets required for product development. Communications are systematically fragmented, which makes any comparison difficult. Furthermore, as analysed earlier, many factors will play a role in either reducing or increasing these costs. For example, greater industrialisation, which requires more investment in the early stages, generally reduces the recurring costs of the product.*

*Physics dictates that the smaller the launcher, the higher the non-recurring development costs per kilogram of launcher (and thus the payload). Furthermore, the absolute values of development costs increase logically with the size of the launcher.*

*It is almost impossible to make a precise estimate of the non-recurring costs (NRC) of the various systems under development, orders of magnitude have nonetheless been derived from known data. For launchers below 100 kg payload (SSO), the order of magnitude is between \$50M and \$100M. For launchers up to 500 kg payload the values range from \$150M to \$400M. Up to 1,000 kg of payload, values range from \$400M to \$800M. These figures include commissioning and production resources (at least for the initial phase).*



As an example, Firefly Aerospace Corporation published (on 27.01.21) a figure of \$200M for the development of their Alpha launcher (supposedly financed by the company's buyers after their bankruptcy in 2016). At the same time, they are looking to raise \$350M for ramping up production (\$125M) as well as for developing a more powerful version with 10 tons of performance (\$225M).

## 7.3 Recurring phase

### 7.3.1 Production rates

Minimising production costs requires optimal use of all resources dedicated to production. One way to achieve this is to strongly standardise products to take advantage of series production effects. This is typically the approach chosen by many players with regard to engines. The launcher and its staging are designed so that the same engine can be used for the two main stages (one for the second stage and six to nine for the main stage). This should ensure minimum costs for this important element in the overall cost equation. A similar approach is possible for large tank structures.

Depending on the type of equipment contracted out, batch purchasing strategies should be compared with continuous purchasing. Larger batches can reduce prices, as long as the availability of the products at all times is assured. For in-house production, continuous occupation of human resources and production means seems ideal, which is easier to achieve with a higher verticalisation of the launcher manufacturer. In this respect the fragmentation of the design and manufacturing activities penalises ESA programmes in terms of costs.

It is important to note that the reuse of launcher components after recovery reduces the production rate and consequently increases the cost of new hardware. Benefits of serial production are driven by the ratio between fix and variable production cost. In addition, there are learning curve effects with growing number of units, thanks to continuous improvement measures. The sizing and the main drivers of the production tool are key decisions to be taken long before the maiden flight. Main drivers are the market analysis and correspondingly forecasted launch rates, but also topics such as workforce flexibility, which are quite different between countries. Also, investment cost amortisation and tax rules impact the business cases.

### 7.3.2 Staging of the launcher, cost by stage/by technology

In terms of cost, the number of stages should ideally be minimised, which runs counter to the performance and flexibility of the launch system. In general, small launchers that are designed for LEO launches have two stages. However, depending on the operational flexibility required, for example for multiple payload launches, it seems useful to have an additional capability such as a powered dispenser, orbital vehicle or kick-stage (e.g. Rocket Lab, RFA). When the first two stages can share many elements for cost reasons, the latter equipment will require quite different propulsion technologies and also very different functionalities and can therefore quickly become a significant cost factor.

*In addition to the technologies already discussed, such as carbon structures, 3D printing and systems electrification, it can be noted that in terms of propulsion, liquid propulsion seems to largely prevail over solid propulsion for commercial ventures. One can note that several Chinese, Indian and a few generally older US launchers use partially or fully solid propulsion. Usually behind this choice, are publicly financed interests to develop and use solid propulsion (dual use) thus sharing its high infrastructure costs. Liquid propulsion makes it easier to increase product performance over time through evolutions of the engines or increasing tank sizes, something which requires substantially more efforts with solid motors.*

### **7.3.3 Recovery and reuse**

*The recovery and reuse of parts of the launcher can reduce the cost per launch of using these elements. However, this depends on the reliability and necessary effort associated with recovery, ease of inspection and post-flight reconditioning, and annual production rates. In any case it means higher initial investments to allow design and qualify the specific features, including the longer product lifetimes. Also, direct operational costs will be higher to include the recovery operations.*

*For example, a mid-flight parachute recovery (Rocket Lab Electron approach tested with two helicopters in April 2020 and parachute descent without recovery tested in November 2020) of a first stage has less impact on its payload performance than the "Toss back" technique, which requires residual propellants and carries with it more risks and operational constraints (weather conditions, flight stability of the stage under parachute, mass of the stage to be recovered...). If one imagines a parachute or even an actively guided parafoil landing, there is a risk of damage on impact with the ground or water. Moreover, contact with salt water makes reconditioning actions more complex.*

### **7.3.4 Sales and marketing**

*The whole area of sales and marketing, funding, insurance and export risk management is often greatly underestimated by newcomers. The skills required are those of operators, not designers, and they are very important for the service offered to customers.*

*The team set up must be able to deal with public clients as well as global, commercial clients. The difficulty will be to make such a team financially viable if launch rates, and thus sales levels, remain low. In this context, customer grouping initiatives (e.g. Exolaunch, Isilaunch) can create value for new entrants who are not yet in a position to hire a highly developed sales force.*

*All small launcher projects also consider rideshare mode to maximise launcher filling. However, this avenue for profitability requires specific commercial action (sometimes carried out by paid brokers) and an orbital stage, both of which increase the cost. A compromise has to be found.*

### 7.3.5 Payload integration

The integration of payloads will systematically require a “clean room” type of environment. The class of cleanliness required may vary depending on the type of satellite, which affects the cost of the infrastructure. The size of the facility will depend on the maximum size of the satellites. Mobile clean rooms are probably possible up to a certain satellite size. The filling of satellite tanks may also require complex facilities depending on the type of propellant chosen.

### 7.3.6 Constraints related to the choice of the launch base

For obvious safety reasons, but also for reasons of access to useful orbits, launch pads are generally located in remote areas. For a launch, it is necessary to be able to transport the launcher by an inexpensive route, but satellites (often at the last minute) by air. Then there are the launcher and satellite teams to be brought in. All of these needs can represent a significant cost, depending on the existing transport infrastructure. All the European bases, whether established (French Guiana space centre) or under development (Andoya in Norway, Kiruna in Sweden and potentially Santa Maria in the Azores) require considerable logistical efforts. Other costly constraints, such as meteorological conditions, may also limit the availability of the base. The geographical position and surrounding inhabited landmasses influence the achievable orbits and can impose trajectory constraints for population safety reasons. So not every orbit can be reached from any launch base. Thus, depending on the orbital inclinations requested by the market, several launch bases (with lower and higher latitude) may be required.

### 7.3.7 Summary of recurring costs

In general, there is limited transparency concerning recurring costs and the launch prices displayed are often questionable before the launchers become operational. The prices initially announced are often loss-leaders based on unrealistic rates that will not be maintained afterwards.

When we analyse the available data, some certain immutable physical principles are reflected. The smaller the launcher, the higher the specific cost per kg launched into orbit. This is linked on the one hand to lower specific performance (kg or % of payload compared to kg of the launcher on the launch pad). On the other hand, the “system” elements such as computers, communication and the electrical systems, required for any launcher create a threshold effect on costs. Compensation for this type of “fixed cost” is usually sought through high launch cadencies.

As a detailed analysis is not possible, orders of magnitude have been derived from the compiled database (for SSO performance):

- $PL < 100\text{kg}$  Price: \$40k to \$80k/kg
- $100 < PL < 250\text{kg}$  Price: \$25k to \$40k/kg
- $250 < PL < 500\text{kg}$  Price: \$25k to \$80k/kg
- $500 < PL < 1,000\text{kg}$  Price: \$15k to \$30k/kg
- $1,000 < PL < 1500\text{kg}$  Price: \$10k to \$45k/kg

*If only operational launchers for which values are available are considered:*

- *PL < 100kg*                      *Price: \$70k to \$80k/kg*
- *100 < PL < 250kg*              *Price: \$25k to \$40k/kg*
- *250 < PL < 500kg*                *Price: \$20k to \$81k/kg*
- *500 < PL < 1,000kg*              *No operational launcher*
- *1,000 < PL < 1500kg*            *Price: \$22k to \$44k/kg*

## **7.4 Funding methods**

*Many of the small launcher initiatives have been promoted and/or incentivised by governments/public actors, using various financial means, like subsidies, participation in the company's capital (or both), early anchor launch orders and many others. This section provides a general overview.*

### **7.4.1 Defence funding**

*On the US defence side, there seems to be a real operational interest expressed in "rapid access to space". To this end, i.e. permanent space presence in all fields, the US-DoD had decided in spring 2020 to financially support 6 new players to the tune of \$116M. They had already chosen the 6 industrialists but without respecting a transparent and objective selection process, which rendered this initiative null and void. In parallel, DARPA has for years been supporting, often confidentially, many promising technological initiatives for future military needs.*

*In Europe, such a doctrine was not yet established in the various member states. In Germany, some of the new players in the small launcher sector have speculated for some time about this "Rapid Access to Space" type of need as one of their commercial axes, but this has not yet been confirmed by the authorities.*

### **7.4.2 Other public funding: national, multilateral**

*In the field of small launchers, it is wise to consider funding of the launch system separately from that of the launch base.*

*In Europe, many states are trying to set up launch bases for small launchers on their territory. Initially, some states (UK, PT) considered that it would be sufficient to create the necessary conditions for business through a space regulation and to secure general infrastructures giving access to a location with appropriate geographical features. Given that the market for small launchers is far from being established and that many countries are rushing into this type of activity, it is increasingly clear that this type of infrastructure only has a chance of being selected by an operator if the investment is carried by the public authorities (Norway, Sweden, etc.), thus minimising recurring costs for the operator. Amortisation of large-scale investment in a base would seem to be impossible through launch prices, which are already under strong pressure due to strong competition.*

*An example is Lockheed Martin (LM), which has contracted a launch with the British government from the Shetland Islands. As there is no significant launch base*

infrastructure there at the moment, LM chose the start-up ABL and its RS1 launcher. The main argument seems to be that this launcher does not require specific ground infrastructure and will be able to transport all necessary equipment in a container. This approach seems promising in terms of fulfilling LM's contractual commitment, but it immediately created a controversy around the UK's economic interest in funding a 100% US-made launch.

As far as launchers are concerned, many states have set up state support programmes that provide a certain level of funding. In countries such as China and Russia, visibility on these types of funding is limited, as the major players are state-owned companies.

In Europe, ESA, within the framework of the last Ministerial Conference in 2019, set up a programme to support the development of small launchers (CSTS launcher programme, with a budget of €50M). Germany, which has made a large contribution (€27M), is encouraging the development of micro-launchers, mainly through start-ups principally oriented to the commercial market. A first round of funding of €500k each out of a €25M global budget was implemented in summer 2020 for three players: Hylmpulse Technologies, Isar Aerospace Technologies and Rocket Factory Augsburg. Two other initiatives were supported by ESA; Orbex with €7.45M, and Skyrora with €3M. Other ESA Member States' investments in demonstrators such as the Prometheus low-cost reusable engine (>€80M) and the Themis reusable first stage demonstrator (>€100M) make it possible to mature technologies fully applicable to future small launcher designs, as one can see with the Morpho concept presented by CNES.

The European Commission organised the European Low-Cost Space Launch Price Initiative (€10M) on 2018, aiming at a European technologically non-dependent low-cost solution for launching light satellites into Low-Earth Orbit (LEO). Furthermore, the European Commission injected €100M into several Venture Capital (VC) funds with a dedicated earmark for Space Start-Up projects. In the new EU MFF budget framework for 2021 to 2027, such cash injection in sectorial VC funds will even be of €1B, with it up to each project to convince the VC funds to finance them.

In the United States, it is also common for civil (NASA) or defence (DoD, DARPA) authorities to inject public funds to encourage the development of certain services, products or innovative technologies. As far as small launchers are concerned, the public authorities in the broad sense seem interested in developing a range of operators in this field. However, they recognise that the commercial market alone will not allow these newcomers to establish themselves or even survive.

To support the new contenders, NASA set up the VCLS (Venture Class Launch Services) programme in 2015 with the selection of three players (Firefly Space System Inc. \$5.5M, Rocket Lab USA Inc. \$6.9M and Virgin Galactic LLC \$4.7M). A second slice: VCLS2 programme was awarded in December 2020 (Astra Space Inc. \$3.9M; Relativity Space Inc \$3M; Firefly Black LLC \$9.8M). NASA's approach is to purchase launch services for Cubesats. These purchases are made early during the development phases on the basis of a call for tender. Nevertheless, the sums

involved remain modest, with \$16.7M in procurement contracts spread over three manufacturers for the VCLS2.

Beyond the above VCLS type of programme, the method of the US administration is to finance and support new actors and concentrate budget on a few selected actors. A key target is always to have at least two fully operational and independent launcher value chains: NASA initiated the Commercial Orbital Transportation Services (COTS) programme in 2006, challenging U.S. private industry to develop cargo and eventually crew space transportation capabilities that meet the needs of ISS. NASA funding would be issued only after the completion of predefined objectives. That was defined as the Phase 1.

In Phase 1, \$500 million were allocated over a five-year period. The Request for Proposals specified that the company be "more than 50 percent owned by United States nationals".

- Two companies were selected among the six finalists: SpaceX (\$278 million) and Rocketplane Kistler (RpK) (\$207 million). The contract with RpK was terminated with a payment of \$32.1 million.
- Orbital Sciences Corp. was the selected one in the Round 2 competition with the remaining funds.
- In 2008, SpaceX (\$278 million) and Orbital were selected for the ISS Commercial Resupply Services contracts.
- In 2009 the COTS budget was increased by \$200 million.
- In 2010 another \$300 million were added to the budget.

At the time of the COTS award, SpaceX was still developing its Falcon 1 small launcher, the first successful launch of which took place on September 28<sup>th</sup>, 2008, and less than two years later the new Falcon 9 was successfully launched.

Afterwards, in Phase 2: the Commercial Resupply Services (CRS) initiative, NASA awarded standard procurement contracts to buy these proven "off-the-shelf" services for delivery of supplies and scientific research experiments to the International Space Station. SpaceX obtained \$1.600M and OSC another \$1.900M.

Russia reorganised its launcher sector around Roscosmos State Corporation in 2015. The drop in income from no longer serving the ISS through the Soyuz launcher, due to the arrival of the US launchers, had a negative impact on the space strategy. Nevertheless, the Russian state announced an amount of €394M, to incentivise initiatives under the scheme of a public-private partnership.

In 2014, the Chinese government decided to treat civil space development as a key area of innovation and issued a policy directive to enable large private investment in companies interested in participating in the space industry. The main players were two state-owned enterprises: the China Aerospace Science and Industry Corporation Limited (CASIC) and the China Aerospace Science and Technology Corporation (CASC). The new commercial launch companies received restricted technologies from military or public entities.



*There are now 78 commercial space companies in China (21 belong to the launcher sector), according to IDA<sup>15</sup>. More than half have been founded since 2014, and the vast majority focuses on small satellites and mini-launchers. Sometimes it is difficult to distinguish their true nature, private or more or less state owned. To mention some, Galactic Energy, i-Space, and LinkSpace may be used as references.*

*The IDA report estimates that Venture Capital funding for Chinese space companies was up to \$516M in 2018. At least 42 companies had no known governmental funding.*

*Generally speaking, it appears clear that the vast majority of small launcher projects are based essentially on private investment. Injections of public funds, as mentioned above, remain marginal in relation to the funding needs required to make this type of launcher operational. This is one of the major challenges for securing funding until completion of the development process.*

### **7.4.3 Private sector, investors, industrial self-funding**

*In the field of private financing a multitude of approaches have already been practised without any particular model standing out. One method of raising funds that seems to be developing recently, particularly in the United States, is through a merger with what is called a SPAC (Special Purpose Acquisition Company). This method consists of merging a company seeking funding (generally with private shareholders) with another company (of the “blank-check” type) specifically created for this purpose, listed on the stock exchange, which has earmarked funds for the purchase of a company but not yet chosen its target (often because a traditional IPO has failed or seems more complicated in terms of upfront financial disclosure and associated valuation).*

*The blank check companies (SPACs) are seen as a route to give investors what they want. The SPAC approach lends itself to doing so in part because it hands much of the risk to these investors. Most notably, because the deal is technically an acquisition, securities regulators allow SPACs to include projected future revenues in their investor pitches, shifting focus away from actual business results. The SPAC’s sponsor and the company it is acquiring can publicly hype their stock in ways not allowed during a typical IPO. And the deals tend to include a large investment of private capital that allows management teams to be more selective about which big investors they bring into their company.*

*This method, which is fairly recent but widely practised and envisaged in the US, is still subject to some controversy in terms of its legality, the applicable publication rules and the transparency of the financial elements (for the “public” shareholders) at the time of the purchase. This type of purchase is often accompanied by a Private Investment in Public Entity (PIPE), a participation of an institutional investor in the contributed capital.*

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<sup>15</sup> “Evaluation of China’s Commercial Space Sector”, September 2019, IDA Institute for Defense Analyses, document D-10873.

*The SPAC approach has recently been implemented by Astra and Virgin Galactic and is currently being considered by Firefly Aerospace to finance the development of its Alpha launcher. Astra has managed to raise \$500M via a SPAC and is valued at \$2B without having made a successful first launch! The €500M cash includes €200M of PIPE from Blackrock.*

*For an established industrialist, the funding for a launcher development should be justified by their available cash/capital (self-financing capacity) on the one hand, and by an amortisation of this investment on the series production costs of the launcher on the other hand, thus penalising its competitiveness.*

*One of the classic methods for start-ups is successive rounds of private funding linked to readiness levels or growth objectives. Typically, these funds are invested or provided by business angels, venture capital or hedge funds, private or sovereign equity investment funds, corporations and others.*

*Funding rounds are identified by letters from A to C or even D/E, which designate increasing levels of maturity and therefore rising associated financial volumes.*

*The profitability of these investments generally seems to be sought by the rapid (exponential) valuation of the company and not by the profits actually generated in the short term.*

*Relativity Space, for example, recently raised \$500M in November 2020 in a D round for the development of its Terran1 launcher and in June 2021 an additional 650M\$ of Series E for the development of a much larger Terran R vehicle. In this case, one can imagine that the lack of maturity of their product and corresponding market would not have permitted an Initial Public Offering (IPO), which is the path most often taken after the C round. The sum of \$500M of D series is nevertheless remarkable considering that the first flight is planned for 2022.*

#### **7.4.4 Two examples of financing cases**

*Compared to the US, the number and financial volume of European Venture Capital funds focusing and investing into Space endeavours is significantly lower. This partially risk adverse behaviours of European VC funds motivated the European Commission to inject some cash in a few selected funds to dynamise this market in Europe.*

*This section is based on some publicly available information regarding the financial investment for two selected US companies.*

##### **7.4.4.1 Relativity Space**

*At end of June 2021, Relativity Space (created in 2015) develops Terran 1, a 2 stages small launcher (1 Ton in LEO), for a first flight end of 2021 and a listed launch price of \$12M. It recently announced the development of a heavy (20 tons in LEO), fully re-usable launcher: Terran R, for a first flight in 2022 (!).*



*Information concerning the funding rounds:*

- *Seed funding: (22.03.2016) \$620K*
- *Series A: (18.07.2016) \$10M*
- *Series B: (27.03.2018) \$350M*
- *Series C: (01. 10.2019): \$140M. This funding was to enable the first flight to be made. It had apparently not yet been fully used by the end of November 2020.*
- *Series D: (23.11.2020): \$500M. The stated aim is to create their production tool, 3D printing facilities and new developments. The general spending plan will not be established until 2021. The financing was provided by 36 investors, of which 7 front line.*
- *Series E: (08.06.2021): \$650M. This latest funding round will make it possible to accelerate development of the Terran R, a vehicle designed to be fully reusable and carry payloads of more than 20,000 kilograms into orbit.*

#### **7.4.4.2 Rocketlab**

*At end of June 2021, Electron (created in 2006) had flown 20 times in all, including its first flight in May 2017. Three launches were failures: the first, the 13th and the last one. Three launches took place in 2018, six in 2019, seven in 2020 and three in 2021. Five full flights were made for US public civil and defence customers and they shared at least one other mission. At least eight launches were rideshare, i.e. multiple launches with very small satellites. Two launches were contracted by foreign private customers (non-US and non-NZL).*

*Information concerning the funding rounds:*

- *Seed (1.01.2006) by 1 Business angel*
- *Series A: (17.09.2013) \$5.5M*
- *Series B: (02.03.2015) Undisclosed amount. This funding was dedicated to completing the launch system development and starting operations in 2016*
- *Series C: (21. 03.2016) Undisclosed amount*
- *Series D: (21.03.2017) \$75M*
- *Series E: (15.1.2018) \$140M*

*The listed launch price was at \$5.7M in 2018. The first Nasa mission in 2018 was valued at \$6.9M.*

*Beyond these past facts one can find interesting additional information on their homepage, where they announce their intention of raising additional capital to become a much larger, verticalised space actor. Looking broadly at their planned evolution from a micro-launcher operator to a large-scale deliverer of space services, it recalls the path of SpaceX. One might wonder if the small launcher is sustainable as a stand-alone business, or if only an integrated, well-developed space services business will secure positive cash flows: "Transaction will provide capital to fund development of reusable Neutron launch vehicle with an 8-ton payload lift capacity tailored for mega constellations, deep space missions and human spaceflight". Funds*

are also expected to finance organic and inorganic growth in the space systems market and support expansion into space applications, enabling Rocket Lab to deliver data and services from space. Rocket Lab forecasts that it will generate more than \$1 billion in revenue in 2026, shared 50/50 between launch activities and space systems and applications. A group of top-tier institutional investors have committed to participate in the transaction through a SPAC (\$320M) and a significantly oversubscribed PIPE of approximately \$470M, with 39 total investors including Vector Capital, BlackRock and Neuberger Berman. The transaction was expected to close in Q2 2021, upon which Rocket Lab will be publicly listed on the Nasdaq under the ticker RKLB. Current Rocket Lab shareholders will own 82% of the pro forma equity of the combined company.

## 7.5 Recommendations for funding in Europe

► **Recommendation No.14:**

*Push for the development of the European ecosystem for public and private capital.*

► **Recommendation No.15:**

*A Public Private Partnership approach could be a viable model for success but requires collaboration between both types of stakeholders.*

## 8 CONCLUSION

*There is a market for launching small satellites. Given the evolution of satellite technologies and the growing interest in space applications, the global market for small (1-500 kg) satellites offers potentially high growth perspectives, even if the uncertainty of the market 10 years from now remains high. While a share of this market will remain captive, and another share will be captured by medium and heavy launchers, there remains room for new solutions. There will also be a need for launching European payloads in the 500 +kg range that require high accuracy in delivery to low Earth orbit.*

*There is a demand for a small launcher service in Europe. The Air and Space Academy and DGLR working group is of the opinion that Europe should add a "small launcher" capacity to its catalogue as a matter of urgency. This is justified by the rising development of new space applications and economy, and the evolution of satellite technologies towards smaller spacecraft. As a consequence, the availability of a "small launcher service" would yield a number of critical benefits: first, allow a real trade-off between fewer, larger satellites and a larger number of smaller satellites with a much-improved revisit time; second, provide significantly cheaper, optimised launch services for European institutional small satellite missions; and third, support the development of the small satellite export market (due to launch constraints on high performance satellites).*

*More than 15 small launcher system projects exist in Europe, from all kinds of competing companies, with creative proposals in terms of technologies, funding schemes and management principles. Such competition, mostly privately funded, increases innovation, challenges existing rules and practices and could provide new solutions, including for potential implementation on bigger launchers.*

*The most competitive and innovative European small launcher projects should therefore be pursued, up to flight demonstration if they pass intermediate steps agreed with investors with the involvement of suitable technical expertise whilst containing associated costs within agreed limits. However, considering the narrow market accessible to Europe, commercially sustainable operations can only be realistically contemplated for a couple of European small launchers.*

*In this context it is in the strategic interest of Europe to ensure that at least one project comes to fruition as soon as possible (say, a first launch within five years) to fulfil the European need for high performance launch services for small satellites that are cost competitive at realistic launch rates.*

*As a result, Europe and its member states should on the one hand continue to play several roles such as supporting technology to foster business development, providing anchor orders under conditions to be formalised, controlling the level of quality and safety, and on the other hand revisit their individual and collective governance and financing models to foster European industry competitiveness.*

*An 800 kg class launcher in SSO 500 km should be developed in Europe, benefitting from an orbital manoeuvre capacity that would allow the launch cost to be shared between several satellites. A rate of around 8-10 launches per year could be achieved, both by guaranteeing the launch of all compatible European institutional satellites and by capturing part of the accessible commercial market for small satellites and some individual satellites above 500 kg. In the €500-800M range, the cost for developing the launch system including production and launch facilities will strongly depend on the technological options, the desired production rate, the conditions imposed by governance and design, safety and certification rules. Institutional support will most probably be needed for the development, through partial funding (PPP), free access to ground facilities and through early guaranteed anchor orders. With a liquid two-stage vertical launch design, compatible with several optional orbital manoeuvring systems, this launcher should be partly re-usable, at least for the first stage if economically justified. The development should target a launch cost in the order of €10M to achieve attractive prices.*

*In addition, a 150 kg class launcher in SSO 500 km orbit could be developed, allowing on-demand launches into a precise orbit. The development of such a launcher (development cost in the €150-200M range), involving competition between several technological innovations (propulsion, structures, manufacturing processes) appears to be compatible with private funding, supporting the development of an eco-system of European space start-ups. The economical sustainability of the exploitation of such launchers will have to be confirmed but validated technologies will have the opportunity to be integrated on future bigger launchers.*

*As a game changer, optional service capabilities for orbital manoeuvrability should be developed for all sizes of launchers including Ariane 6 and Vega C to launch several small satellites into various orbits, with an improved accuracy.*

*The European small launcher ecosystem needs to be fostered. Being in a transition phase, the final public and private solution remains to be defined and implemented, but European actors must definitely bet on the success of future small launchers. In parallel there are a number of initiatives to invest in launch sites from Europe. In spite of the limited orbit characteristics the proposed new sites can support, the initiatives foster new concepts and ideas on ground means and safety approach that need to be fed into existing facilities in French Guiana, which would thus become more pragmatic and cost effective.*

## **ANNEX 1 PARTICIPANTS IN THE WORKING GROUP**

*Under the lead of Alain Charmeau, a joint AAE-DGLR working group brought together members of French, German, Italian and Spanish nationalities:*

- *from AAE: Jürgen Ackermann, Christophe Bonnal, Gérard Bréard, Jean Broquet, Alain Charmeau, Michel Courtois, Gérard Frut, Antonio Fuentes, Ralph Jaeger, Wolfgang Koschel, Alain de Lefte, Marcello Onofri, Alain Ratier, Bruno le Stradic;*
- *from DGLR: Ludger Froebel, Rolf Janovsky;*
- *supported by Francesco Nasuti, from Sapienza University of Rome.*

*The working group had the honour and the privilege to meet with external contributors and would like to thank for their participation:*

- *Murielle Lafaye, CNES;*
- *Jean-Jacques Dordain;*
- *Dmitriy Bogdanov (CEO), Jeanne Medvedeva (VP Sales), ExoLaunch.*

## ANNEX 2 GLOSSARY

AAE	<i>Académie de l'air et de l'espace – Air and Space Academy</i>
ADS-B	<i>Automatic Dependent Surveillance – Broadcast</i>
AIS	<i>Automatic Identification System, tracking system used for vessel traffic services</i>
AOS	<i>Additional Optional Stage</i>
COTS	<i>Commercial Orbital Transportation Services</i>
CRS	<i>Commercial Resupply Services</i>
DCS-B	<i>Digital Communication System</i>
DGLR	<i>Deutsche Gesellschaft für Luft- und Raumfahrt</i>
ESA	<i>European Space Agency</i>
ELINT	<i>Electronic Intelligence</i>
IoT	<i>Internet of Things</i>
IRL	<i>Industrial Readiness Level</i>
$I_{sp}$	<i>Specific Impulse</i>
ISS	<i>International Space Station</i>
LEO	<i>Low Earth Orbit</i>
LOx	<i>Liquid Oxygen</i>
OMV	<i>Orbital Manoeuvring Vehicle</i>
PIPE	<i>Private Investment in Public Entity</i>
PL	<i>Payload</i>
RAAN	<i>Right Ascension of the Ascending Node</i>
RP1	<i>Refined Petroleum 1 Kerosene</i>
SPAC	<i>Special Purpose Acquisition Company</i>
SSO	<i>Sun Synchronous Orbit</i>
TRL	<i>Technology Readiness Level</i>
TSTO	<i>Two Stages To Orbit</i>
VC	<i>Venture Capital</i>
VCLS	<i>Venture Class Launch Services</i>

## **ANNEX 3    DEFINITION OF SMALL SATELLITE CATEGORIES**

*Classes of small satellite differ between sources of information. A generic classification can be presented as follows.*

- **Picosat:** mass from 0.1 kg to 1 kg;
- **Nanosat:** mass from 1 kg to 30 kg. Most nanosats are in the “Cubesat” standard. A “Cubesat” is characterised by a number of units: “U”, typically from 1 to 12 U. One unit is defined as a cube of 10 cm side and a mass from 1 to 1.5 kg;
- **Microsat:** mass from 30 kg to 100 kg. They can be part of the “Cubesat” standard when their mass is slightly above 30 kg;
- **Minisat:** mass from 100 kg to 500 kg (even up to 600 kg in some cases). Most of the time their architecture is derived from bigger satellites, with downscaled equipment and sub-assemblies.

## **ANNEX 4    WORKING GROUP MISSION STATEMENT (February 2021)**

*Since a few years, technological evolutions have allowed the use of small satellites for numerous and more and more efficient applications. Interest for use of these satellites has increased for new countries willing to own access to space or to develop a space ecosystem, for institutions, universities, industries and private investors such as for telecommunications.*

*The diversity of types of small satellites, in terms of mass, volume, orbits, quantities has led to a significant evolution of the solutions to launch these satellites. Heavy launchers proposed adaptations to launch clusters of dozens of satellites, and a high number of projects of new small launchers have appeared, together with several projects of new launch sites.*

*It appeared useful to the Space Committee of the AAE Academy and the DGLR to elaborate a Dossier to analyse the existing situation in terms of launch systems for small satellites in the range 10 to 500 kg.*

*For launchers in the range of 300 to 1500 kg in SSO orbit, the dossier will be about:*

- understanding of the market, customers, and users;*
- identification of projects worldwide, for launchers and launch sites;*
- launcher's technologies;*
- global industrial landscape;*
- exiting or foreseeable financial schemes;*
- nonrecurring and recurring cost factors.*

*For this purpose, the AAE Space Committee, in association with the German DGLR decided to set up an international working group.*

*Under the lead of A. Charmeau, the members of the working group are Msrs J. Ackermann, C. Bonnal, G. Bréard, J. Broquet, M. Courtois, A. Fuentes, L. Froebel, G. Frut, R. Jaeger, R. Janovsky, W. Koschel, A. de Leffe, F. Nasuti, M. Onofri, A. Ratier, B. le Stradic.*

*The dossier will be presented to the AAE Space Committee during the third term of 2021. As far as possible but depending on the progress of the work the working group will elaborate proposals or recommendations.*

Philippe Couillard

Alain Charmeau



## ANNEX 5 SMALL SATELLITE LAUNCH MARKET BY THE LATE 2020s

### A 5.1 OVERVIEW/TOP-DOWN APPROACH

The small satellite market information used for this top-down approach was collected from articles and information found on the internet or by participating in conferences or other types of meetings. Most of the original material synthesised in this chapter came from market analysis firms, in particular Euroconsult and to a lesser extent Bryce, Northern Sky Research (NSR) and PricewaterhouseCoopers (PwC).

#### A 5.1.1 Evolution of the total number of small satellites launched worldwide

The main trends shown in different forecasts done in 2019 by specialised firms are presented in Figure A5-1 (All values have been smoothed in order to better reflect trends. Since the purpose is to show the similarities of these forecasts, each curve is not explicitly linked to each source).

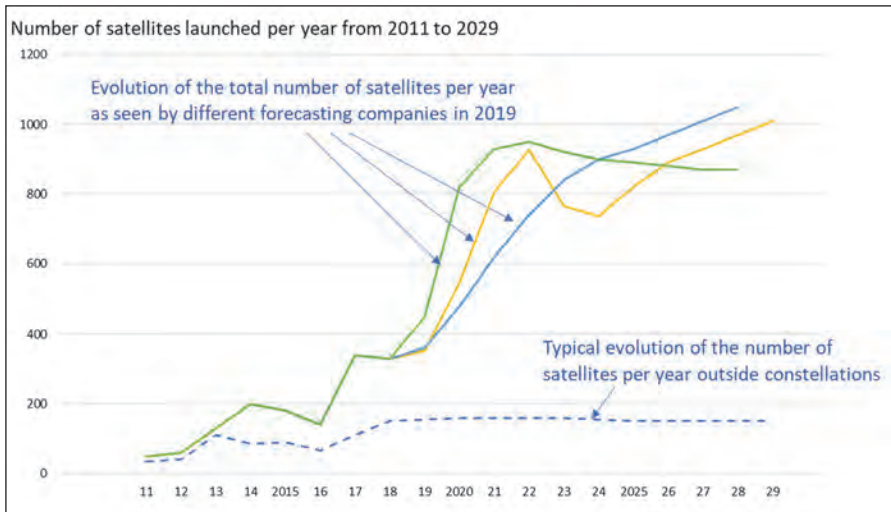


Figure A5-1: Number of small satellites (< 500 kg) launched per year until 2018 or 2019 and forecasts beyond. Initial sources: Data from Euroconsult, PwC and NSR found in different articles on Websites.

About 1600 small satellites were launched over the 2009-2018 period. About 9,000 satellites are forecast during the period 2019-2028, half of which in broadband communication constellations.

The slight differences between the forecasts issued by the various market analysis companies reflect the level of uncertainty on the current state of play of known projects today and the high volatility of the launch dates. The very strong dynamic of change in the field of small satellites greatly contributes to forecasting uncertainties.

### A 5.1.2 Evolving number of small satellites by application domain

Evolution forecasts between the decades 2009-2018 and 2019-2028 are shown in Figure A5-2.

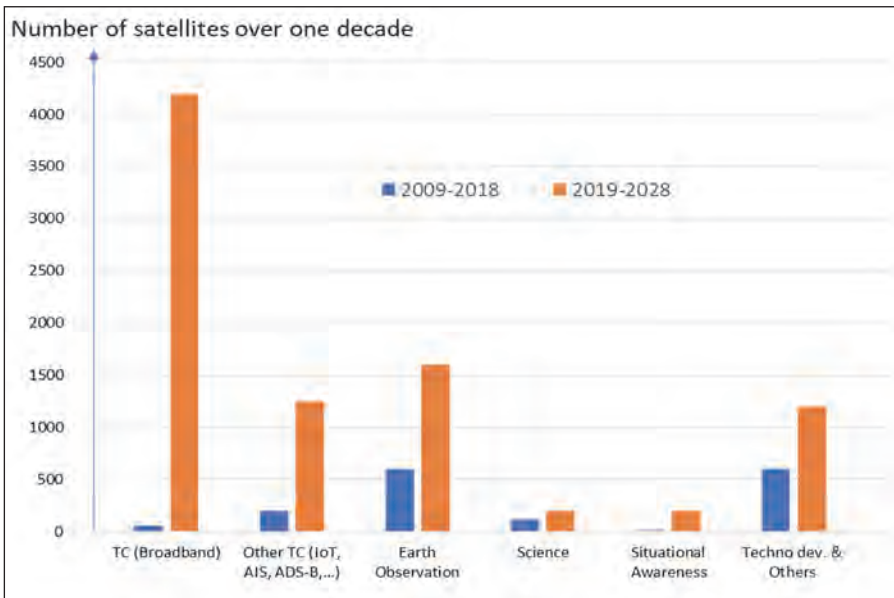


Figure A5-2: Annual number of small satellites injected into orbit by application domain (actual before 2019, forecasts after).

A steep increase in the number of satellites is forecast for telecommunications, particularly broadband, and also for the Internet of things.

Although at a lower rate, the market for Earth observation data and services could grow by 8-10% per year on average over the decade 2020-2029. According to market analysis firms, Earth observation satellites represent more than 100 tons to be launched over the current decade.

In the area of technology demonstration and new services, some forecasts anticipate the launch of over 1,200 satellites over the period 2019-2028, with an average mass per satellite of 25 kg, i.e. 30 tons in total.

Limited growth is anticipated for scientific minisatellites with the launch of 150 satellites over the period 2019-2028, and an average mass per satellite of 100 kg, or around 15 tons in total.

### A 5.1.3 Launch market for small launchers

When looking specifically at the launch market for small launchers, the numbers of small satellites should be identified by mass range.

We also note with the launches of Starlink (with SpaceX, Falcon 9) and OneWeb (with Arianespace, Soyuz) that broadband communication satellites should not be considered as part of the potential launch market of small launchers (at least for most launches).

After compiling useful information from different available sources, the worldwide market for the launch of small satellites over the period 2025-2030, excluding broadband telecommunication satellites, has been estimated as follows:

Satellite unit mass ranges	Forecast cumulative mass of satellites to be launched per year
< 10 kg	~ 1 ton
11 to 50 kg	~ 3 tons
51 to 250 kg	~ 9 tons
251 to 500 kg	~ 11 tons

Table 7: Forecast of cumulative mass of satellites to be launched per year.

## A 5.2 FORECAST FOR SMALL SATELLITES WORLDWIDE BY THE LATE 2020S – Bottom-up approach by area of application

Most of the information in this chapter on small satellite projects and programmes dates from late 2020 or early 2021.

### A 5.2.1 Constellations of small satellites in low Earth orbit for broadband telecommunications

Telecommunications satellites are generally categorised according to their main applications: broadband for the Internet, wideband for mobile telephony and narrowband for the Internet of Things (IoT), including Machine to Machine (M2M) links and similar specialised services such as AIS for ships and ADS-B for aircraft.

Satellite constellations for telephony, such as Iridium and Globalstar 2nd generations, use satellites with masses of 860 kg and 700 kg respectively. Next generation satellites are not currently advertised as small satellites.

Small satellite constellations for narrowband communications are presented in section A 5.2.3.

In broadband telecommunications, satellite launches into low-Earth orbits over the next 4-5 years are unlikely to be representative of future developments in the same application

area. The number of commercially viable or government-supported constellations is difficult to predict. So is the mass of the satellites in these constellations.

Current projects are shown, by country, in Table 8:

Country of operator	Constellation project name	Unit mass (kg)	2019-2023		2024-2028		Launcher
			Nb of satellites	Total mass (tons)	Nb of satellites	Total mass (tons)	
US	Kuiper	300			1250	375 t	Blue Origin
	Starlink	227	1200	272 t	420	95 t	SpaceX
UK/India	OneWeb	145	644	93 t	65	9,4 t	Arianespace Soyuz
China	GuoWang (formerly Hongyan & Hongyun)	200?	> 1000				Chinese launcher
Canada	Telesat	700	78	55 t	220	154 t	
Russia <sup>23</sup>		?					
Europe <sup>24</sup>		?					

**Table 8: Constellations of small satellites in low Earth orbit for broadband telecommunications.**

All these satellites are launched (or likely to be launched) by medium and heavy launchers.

### A 5.2.2 Small satellites for Earth observation

Civil government and defence customers will likely continue to play a key role in market growth and over 50 countries may have launched at least one satellite by 2028. However, the vast majority of satellites in constellations will be operated by commercial companies.

Non-governmental opportunities are emerging in the financial, insurance, maritime and energy markets. The use of data in machine learning and "big data" in general will absorb volumes of data far beyond what is available today, of varying quality. Small satellite constellations in operation or in the planning stage are most often intended to complement data obtained by "traditional" satellites. Missions are diversifying in the field of optical observation:

- panchromatic and multispectral images, with different compromises between resolution, speed of access on demand and/or revisit;
- hyper-spectral images or images with a few dozen spectral bands selected according to the application;

<sup>23</sup> Russia is considering the development of its own space system.

<sup>24</sup> The European Commission is analysing the conditions for deploying a constellation under the control of a European operator.

- *infrared images including Thermal InfraRed (TIR);*
- *video.*

*They are also diversifying into the field of radar observation (X or L band Synthetic Aperture Radar) which has become accessible to microsatellites.*

*Programmes and projects are also differentiated by levels of technological innovation and reduced infrastructure costs, as well as by the vertical integration model with services and access to customers.*

*The following tables give a view on the variety of missions and related projects. The overview is based on internet data of programmes and projects identified at the end of 2020 or mid 2021.*

*Most Earth observation satellites in constellations of more than six satellites (except the Chinese Jilin video satellites) have a unit mass of less than 120 kg.*

*The very significant increase in the number of small satellites expected over the next decade for Earth observation is mainly due to the emergence of constellations populated by nano or micro satellites.*

*Constellations with only few satellites, such as CO3D, or missions with a single satellite (e.g., export for civil or dual-use applications) most often use minisatellites with masses between 200 and 600 kg) or even medium satellites (mass between 600 kg and 1,000 kg).*

*Given ongoing technological developments, the volume of the minisatellites market, and therefore also the corresponding launch market, is expected to increase significantly.*

*The civil and military governmental market can be estimated at 10 satellites with a typical mass of 250 kg per year over the next decade.*

*The total mass of small satellites for Earth observation is estimated at over 8 tons on average per year (of which 40 % for China) for satellites in constellations to be launched in the period 2021-2025.*

*Assuming an equivalent mass of satellites in constellations to be launched over the period 2026-2030, and with an average of 10 satellites of 250 kg per year outside constellations, the total mass to be launched over this period is of the order of 10 t per year.*

*The majority of these satellites (likely more than 60 %) will be placed in sun-synchronous orbits. Only a relatively small proportion of the launches are available to Europeans.*

Constellation name	Mission Pan : Panchromatic, 3D : 3 Dimensions; m : Resolution in meters	Satellite unit mass (kg)	Number of satellites in the constellation
Satellite unit mass range : 251 to 500 kg			
CO3D	Imaging Pan 0.5m, 3D	300 kg	4 (potential extension)
Jilin Optical	Imaging (Pan 0.72m, Multispect)	420	4
Jilin video	Colour video	208	69
Other projects	Imaging (Pan 0.5m, Multispect)	300 to 500 kg	?
Satellite unit mass range : 51 to 250 kg			
Blacksky	Imaging (Pan 1m, multispect)	55	60
GRUS (Axelspace)	Imaging (Pan 2.5m, IR)	80	3?
Canon	Imaging (Pan 0.9m), Video	67	Up to 100
Earth-i/Vivid-i	Colour video	100	15
Planet HD Skysat	Imaging (Pan 0.72m, Multispect)	120	21
Land Mapper-HD, Astro-D	Imaging (Red, Green, Blue 2.5m)	20 kg /16U	20
Others : ex. DMC	Imaging (Pan 1m)	70	9 sats launched < 2019
Zhuhai (several constellations)	Imaging (Hyperspectral), Imaging (IR), Video	50 to 90 kg	Up to 30 satellites in total
Satellite unit mass range : 11 to 50 kg			
Aleph/Satellopic	Imaging (Pan 0.7m, Hypersp 30m, TIR 90m), Video (HD)	37	90
Hera	Imaging (Multispect 1m)	22	50
Promethee	Imaging (Pan <1 m)	35	20 (up to 80?)
Satellite unit mass range : < 10 kg			
Planet Flock Dove	Imaging (Pan 4m, Multispect)	6 kg/ 3U	250
Land Mapper-BC, Astro-D	Imaging (RGB 25m)	~10 kg/ 6U	12

■: Chinese programmes or projects. / ■: Companies with headquarters in Europe.

Table 9: Constellations of satellites for optical Earth observation (Panchromatic and multispectral, hyperspectral, video).

Constellation name	Mission	Satellite unit mass	Planned (or potential) number of Satellites in the constellation
All known minisatellites projects are based on satellites with a unit mass range : 51 to 250 kg			
ICEYE	SAR (X band , 1 m to 0.25 m)	70 kg	20
Capella	SAR (X band, 1 m)	52 kg	36
Umbra	SAR (X band, 1m to 0.25 m)	50 kg	12
Synspective (Japon)	SAR (X band, 1m)	150 kg	30

■: Company with headquarters in Europe.

Table 10: Constellations of satellites for Radar Earth Observation.

Constellation name	Mission	Satellite unit mass	Number of Satellites in the constellation
GHGSat	Methane detection	18 kg	3 or more
PlanetIQ	Weather measurements (Radio Occultation GPS)	30 kg	20
Spire	Weather measurements (Radio Occultation GPS) + (see chapter 2.3)	< 5 kg/3U	> 150
Cicero GeoOptics	Weather measurements (Radio Occultation GPS)	~10 kg /6U	? 7 already launched
Orbital Micro Systems	Weather measurements (micro-waves)	< 5 kg/3U	40

Table 11: Constellations of satellites for other Earth observation services.

### A 5.2.3 *Small satellites for narrow-band communications (Internet of Things, signal detection, location and others)*

Applications such as the Internet of Things, AIS, ADS-B and frequency monitoring can be grouped under the heading of "Information" used by Euroconsult.

With the exception of China, programmes and projects call for very small satellites of the nanosatellite type (mass < 30 kg) or even in some cases of the pico satellite type.

The vast majority of Information satellites are deployed in constellations and are operated by commercial companies. Most of them are potentially in the open launch market.

Constellation name	Mission	Satellite unit mass	Potential Nb of satellites in constellation
<b>Satellite unit mass range : 51 to 250 kg</b>			
CASIC Xingyun	Internet of Things (IoT)	93 kg	80
<b>Satellite unit mass range : 11 to 50 kg</b>			
Kineis	Internet of Things (IoT)	27 kg	25
Kleos Space	Detection/local. of RF signals	12 kg	40
Hack Eye 360	Detection/local. of RF signals	13	21
Skywalker (Head Aero)	IoT, AIS, ADS-B	45 kg	48
<b>Satellite unit mass range &lt; 10 kg</b>			
Spire	AIS+ADS-B+ (see Earth Obs)	5 kg /3U	see Earth Obs)
AistechSat	IoT, M2M, AIS, ADS-B, IR imaging	2U/ 6U	100
Unseenlabs	Detection/local. of RF signals	6 kg	25
Hiber	IoT	3U/6U	48
Astrocast	IoT, M2M	3U	80

■ : Chinese programmes or projects. / ■ : Companies with headquarters in Europe.

Table 12: Overview of the main current constellation programmes and projects.



#### **A 5.2.4 Small satellites for security (Space and space environment monitoring, navigation, early warning, ELINT)**

*In the field of security, forecasts have changed significantly during the last few years due to the emergence of new defence requirements.*

*A current assessment would be in the range of 200 satellites or more with an average mass per satellite of 200 kg (40 tons in total) to be launched over the period 2019-2028 for all security and ground-based defence support applications.*

##### **A 5.2.4.1 Global dual (civil and defence) space surveillance**

*Space Situational Awareness (SSA) is being developed in both civilian and defence sectors, with some countries adding specific defence components.*

*Several space surveillance projects based on constellations of small satellites could emerge. Of particular note is NorthStar's Skylark project, which is awaiting development. The satellite unit mass could be of the order of 100 kg and the constellation could include up to 40 satellites.*

##### **A 5.2.4.2 ELINT, early warning, navigation**

*The use of small satellites for these applications must be analysed on a case-by-case basis.*

*In France, the three electronic surveillance satellites to be launched in 2021 have a mass of ~450 kg.*

*In the field of navigation, the United Kingdom is currently considering the development of capabilities with OneWeb first or second generation mini-satellites.*

##### **A 5.2.4.3 Active satellite protection**

*By way of illustration, the current thinking on the French side is that " ... Nanosatellites will be responsible for active protection from space of the most critical satellites for the armed forces". Extract from the Defence Space Strategy report 2019, available on the Internet, of the Ministry of Defence (courtesy translations): "Small launcher projects have the ambition to offer a launch service with a better reactivity than the one offered by traditional launch operators... This is why the armies will study the opportunity to use a possible reactive launch capability ("quick launch") adapted to small satellites".*

#### **A 5.2.5 Other areas of application for small satellites**

##### **A 5.2.5.1 In-orbit technology tests and new services**

*Primarily initiated by governments and universities, projects in this area are now expanding quite significantly with capture and repositioning and/or de-orbiting, propellant replenishment and in-orbit repair demonstrations.*

### A 5.2.5.2 *Science and exploration*

*The improved capabilities of small satellites should result in a greater use of such satellites and an increasing number of national initiatives in science and exploration.*

### A 5.2.5.3 *Other: In-orbit data storage*

*In-orbit data storage is one of the new types of space-based services under investigation. As a typical example: Cloud Constellation Corporation is building SpaceBelt, a data storage and global connectivity service. The current plan is for 12 small satellites (with a unit mass of around 140 kg) in equatorial orbits, with optical inter-satellite links.*

### A 5.2.5.4 *The case of small satellites in medium, geostationary or elliptical orbits*

*A number of small satellites (typically more than 100) are expected to be launched into non-LEO orbits over the next 10 years. For example, in 2019 the US Air Force placed two space surveillance satellites of less than 100 kg into a geostationary orbit. A French demonstrator "Yoda", based on two nanosatellites, will be launched in 2023 into GEO orbit, preparing for an operational system in 2030.*

## **A 5.3 SMALL SATELLITE MARKET ACCESSIBLE FOR A EUROPEAN LAUNCHER BY 2025-2029 –Bottom-up approach**

### **A 5.3.1 Launches on the initiative of European operators**

*Euroconsult 2019 puts the mass of small satellites to be launched over the decade 2019-2028 by European governments (civil or defence) and European commercial operators at ~ 30 tons.*

*A very rough bottom-up assessment of the types and mass (above 10 kg) of satellites meeting these criteria can be made on the basis of:*

- *current, emerging or potential commercial initiatives;*
- *observable developments in Europe in the programmes of national civil agencies;*
- *foreseeable developments in the programmes of defence organisations;*
- *evolution of satellite sizes for ESA missions, on the initiative of ESA.*

#### **A 5.3.1.1 Commercial Earth Observation and Information applications**

*Commercial programmes and projects constellations of small satellites with European operators (or those with a strong commercial component), over the 5-year period from 2021 to 2025, represent a launching mass of almost three tons for Earth observation and nearly 1.3 tons for Information applications. The expected increase in European initiatives (similar to the growth in the development of small launchers in Europe today) could therefore lead to a total mass of over five tons to be launched over the 5-year period from 2026 to 2030, for Earth observation (mostly into sun-synchronous orbits) and Information (mostly into inclined orbits, other than sun-synchronous).*

A typical average launch scenario includes 1.5 t of satellites per year, typically for Radar Earth observation (e.g. ICEYE type), Visible and IR Optical E-O (e.g. CO3D type), Hyper-spectral optical E-O (e.g. Satellogic type), and Internet of Things (e.g. Kineis type).

#### *A 5.3.1.2 Small satellites launched at the initiative of national civil agencies and ESA*

*More and more European countries are taking advantage of the capabilities of small satellites for science, technology demonstration and Earth observation to extend their sub-system designer and manufacturer capabilities to that of prime contractor. This trend, observed over the last three decades, is expected to increase in the coming years.*

*Likewise, ESA could make greater use of small satellites for scientific missions and for technological demonstration missions on the themes mentioned in Chapter 2 of this annex, such as deorbiting, capture and repositioning and in-orbit propellant resupply.*

A typical average launch scenario for ESA and the Member States includes 1 t of satellites per year.

#### *A 5.3.1.3 Small satellites for security and defence*

*Various developments are possible over the next decade, such as the emergence of satellite constellations for space surveillance, and satellites to ensure the security of defence space infrastructures.*

A typical average launch scenario includes 0.5 t of satellites per year, typically for Electromagnetic listening and Intelligence and Space Surveillance Awareness.

### A 5.3.2 *Synthesis: Scenario for the number and mass of satellites on the open launch market for small launchers by 2025-2029 (yearly average)*

To sum up, an estimate of the satellites available for commercial launches by 2025-2029 (including satellites operated by European companies) is given, as a yearly average, in Table 13.

Mass range	European operators		Worldwide inc. Europe (open market)	
	Number of Sats /year	Total mass	Number of Sats /year (% of satellites in constellation)	Total mass
1-10 kg		< 0.2 t		< 0.3 t
11-50 kg	25	1t	50 (80% in const. of more than 20 satellites)	2t
51-250 kg	10	1t	30 (70% in const. of more than 8 satellites)	3t
251-500 kg	3	1.2t	5 (20% in const. of at least 4 satellites)	2t
500-1000 kg	3	2t	5	3t

*Table 13: Satellites open to commercial launches by 2025-2029 on average per year.*

In the table above, satellites within the mass range of 500-1,000 kg have been included, since the comparison between launchers is not limited to a capacity of 500 kg.

In this mass range, according to available satellite forecasts, the average annual launch of satellites worldwide (always excepting broadband communications) could, by the end of the 2020s, reach:

- 10 to 20 Earth observation satellites in low Earth orbit (e.g., Worldview, Xpress SAR);
- 5 to 10 scientific or technology demonstration satellites;
- 2 to 3 satellites per year for security;
- 1 satellite every few years for other applications.

## **ANNEX 6    ORBITAL MANOEUVRE PRINCIPLES AND TYPICAL PERFORMANCE**

### **A 6.1    MANOEUVRE PRINCIPLES**

#### **A 6.1.1    Changes in orbit inclination or in orbit altitude/semi major axis**

*Such changes can only be performed through a well-known, unique type of manoeuvre (with spreading of thrust according to duration and efficiency criteria).*

#### **A 6.1.2    Changes in RAAN (Right Ascension of the Ascending Node)**

- *Changes in RAAN by up to 20 degrees or more by direct transfer from initial to final orbits are generally not possible (except for orbits with low inclinations) due to the need for extremely high  $\Delta V$  ( $\Delta V$  is for change in satellite velocity).*
- *Change in the RAAN between orbits of the same inclination by creating a drift.*

*It is always possible, by temporarily changing either the orbit semi major axis or the orbit inclination, but taking weeks or months, to reach a RAAN change of several tens of degrees. The efficiency of altitude manoeuvres to create RAAN drift increases with the cosine of the orbit inclination, so that for polar orbit, the only possibility is to change the inclination.*

*The orders of magnitude of the relative drift speeds of the RAAN as a function of changes in inclination or altitude are shown in the figures below.*

*As shown in Figure A6-1, the orbit altitude is limited by aerodynamic drag on the one side and radiation level on the other, to the range of typically ~250 km-1500 km.*

*The RAAN manoeuvre consists of starting from the initial Sun Synchronous Orbit (SSO), changing the inclination/altitude (plus or minus according to the sign of requested local time change) so as to obtain an intermediate orbit whose RAAN is shifting with respect to that of the initial SSO, waiting for the desired cumulated drift and finally returning to the SSO inclination/altitude before releasing the payload.*

In order to minimise the consumption of propellant, the choice of an inclination rather than an altitude manoeuvre, or vice versa, can be made according to the initial inclination of the orbit (see above figures) given that, at an altitude of about 500 km, the  $\Delta V$  required for:

- altitude change of 100 km is  $\Delta V \sim 53$  m/s;
- inclination change of  $1^\circ$  is  $\Delta V \sim 132$  m/s.

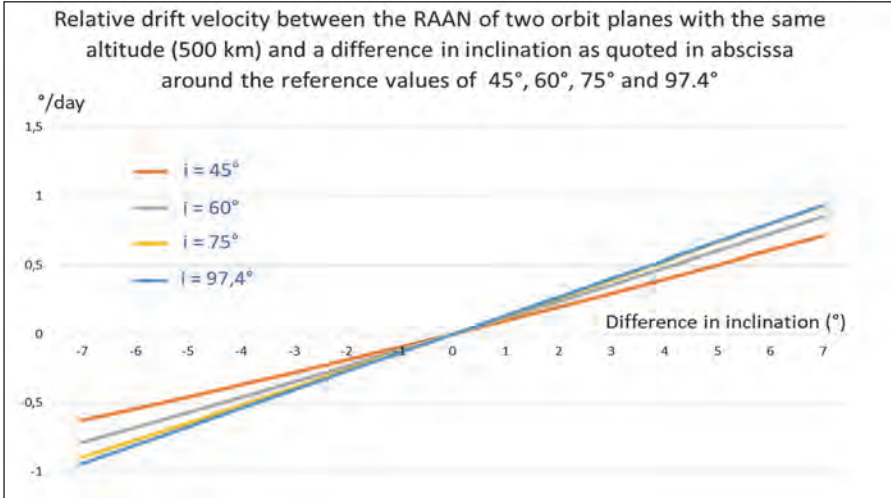


Figure A6-1: Relative drift velocity between two orbits with the same altitude.

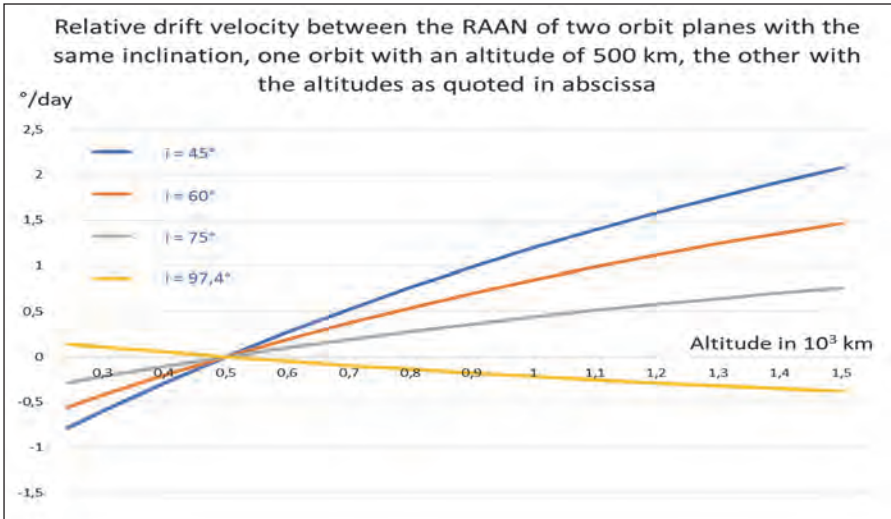


Figure A6-2: Relative drift velocity between two orbits with the same inclination.

## A 6.2 TYPICAL PERFORMANCES

### A 6.2.1 Orbital manoeuvres with a launcher Additional Optional Stage (AOS)

A launcher additional stage with chemical propulsion can be used to obtain relatively large orbital manoeuvring capacities at the expense of significant propellant mass. Chemical propulsion offers specific impulses up to more than 300 sec and thrust level of several tens of Newtons. The dry mass of the AOS (outside payload) can be of the order of 200 kg to 300 kg respectively for launchers with capacities 500 kg to 1,000 kg.

#### A 6.2.1.1 Change in orbit inclination

Manoeuvring capability is illustrated in Figure A6-3 for an AOS dry mass of 250 kg, assuming that, at launch, the available mass, on top of the primary payload is used for a secondary payload ("mass of payload" in Figure A6-3) and for additional propellant and tanks devoted to an orbital manoeuvre (change in inclination). The propulsion  $I_{sp}$  is taken as 300 sec, and the mass of the tanks is taken as 15 % of the total mass for tank and propellant used for the manoeuvre.

The duration of the manoeuvres for changing the inclination is limited to a few days (several bursts of total duration of up to few hours).

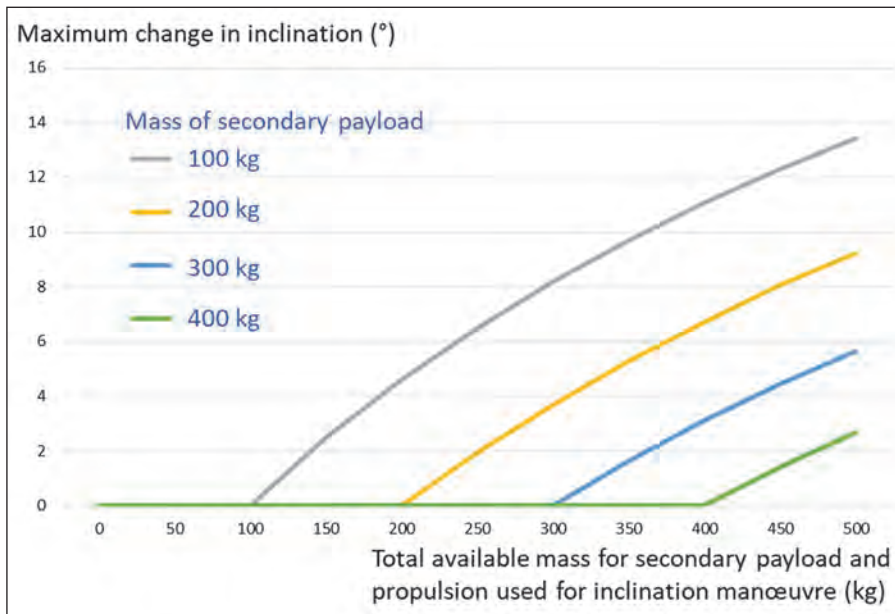


Figure A6-3: Change in the Mean Local Time (MLT) of a SSO by creating drift of the RAAN through inclination change manoeuvres.

The duration of the manoeuvre is mainly determined by the duration of the drift phase which itself depends on the maximum inclination change (as shown in the

figures in Chapter 1). As an example, with a maximum inclination change of  $\pm 3.5^\circ$ , at constant altitude, the duration of the manoeuvre would be about 45 days for  $\Delta(\text{MLT})$  of  $20^\circ$ .

### **A 6.2.2 Large orbital manoeuvres with transfer modules with electro-thermal propulsion**

Two illustrations of the capacities of manoeuvre of transfer modules are given for a transfer module dry mass (including tanks) of 70 kg (excluding Payload), a propellant mass of 30 kg, a payload mass of 50 kg, and a propulsion  $I_{sp} = 700$  s.

The manoeuvre duration is defined with realistic assumptions as to the electrical power available for propulsion, electrical power efficiency of the propulsion system, and geometric efficiency for inclination changes (due to the thrust being spread out around the optimal thrust positions along the orbit). A thrust level of  $\sim 75\text{mN}$  was selected.

- Example 1: Change in orbit inclination: up to  $\Delta i \sim 9.5^\circ$ . Duration of the manoeuvre:  $\sim 50$  days.
- Example 2: Change in Mean Local Time of an SSO by creating drift through inclination change manoeuvres ( $\pm 4.75^\circ$ ), at constant altitude: Duration of the manoeuvre: about 2 months for  $\Delta(\text{MLT})$  of  $20^\circ$ .

Penalties when using orbital transfer modules with electric propulsion for secondary payload:

- mass to be launched (typically an additional mass of 2 times the secondary payload mass);
- cost of transfer module and operations;
- manoeuvre duration (several months for large manoeuvres).

### **A 6.2.3 Small orbital manoeuvres with transfer modules with chemical propulsion**

To illustrate, let us consider a platform with a dry mass of 55 kg excluding payload, a maximum monopropellant propellant mass of  $\sim 17$  kg ( $I_{sp} \sim 220\text{s}$ ), and a total payload mass of  $\sim 200$  kg.

This module allows inclination changes of the order of  $1^\circ$  for the payload of 200 kg. It can be used notably for altitude change of the order of 250 km or for the positioning of several satellites (parts of the 200 kg payload) along the orbital injection plane.



## ANNEX 7 DATABASE OF LAUNCHERS<sup>25</sup>

### A 7.1 NUMBER OF LAUNCHERS BY GROSS PAYLOAD MASS AND COUNTRY

Country	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450	451-500	501-550
Argentina	1		1								
Australia	1				1						
Brazil	1										
Canada			1								
China		1	1	4	3	2		1		2	
Europe						1					
France		1		2						1	
Germany								1			
India			2	1	1	1			1		
Iran	2	1					1				
Israel								1			
Italy	1										
Japan	1	1	1						1		
Malaysia				1							
Netherlands		1									
North Korea				1							
Norway					1						
Philippines				1							
Russia		2	1							1	
Singapore			1								
South Africa											
South Korea	1									1	
Spain	1	1	1						1		
Sweden			1								
Taiwan				1							
UK		2	1			1	1				1
USA	6	5	2	3		4	1	2	1	2	
<b>TOTAL</b>	15	15	13	14	5	10	3	5	3	7	1

Table 14: Number of launchers by gross payload mass and country, mass range 0-2200 kg.

<sup>25</sup> For optimal lisibility, all tables below are spread over a double page, in English version only.



Country	2.251-2.300	2.351-2.400	2.650-2.700	2.851-2.900	3 200	3 450	3 600	4 400	5.000-5.500	6 450	7 300
Argentina											
Australia											
Brazil											
Canada									2		
China	1	1		1					1		1
Europe		1	1							1	
France											
Germany											
India											
Iran											
Israel											
Italy											
Japan											
Malaysia											
Netherlands											
North Korea											
Norway											
Philippines											
Russia								1			
Singapore											
South Africa											
South Korea											
Spain											
Sweden											
Taiwan											
UK											
USA					1	1	1			2	
TOTAL	1	2	1	1	1	1	1	1	3	3	1

Table 15: Number of launchers by gross payload mass and country, mass range >2200 kg.

8 750	10 500	13 150	13 930	14 900	15 420	15 700	22 850	Total	Status
								2	Dev.
								2	Dev.
								1	Dev.
								3	Dev.
1					1			29	18 Oper - 11 Dev
				1		1		7	2 Oper. - 5 Dev
								5	Dev.
								3	Dev.
								8	1 Op - 6 Dev - 1 Ret
								4	3 Oper - 1 Dev
								1	Oper.
								1	Dev.
								4	2 Oper - 2 Dev
								1	Dev.
								1	Dev.
								1	Oper.
								1	Dev.
								1	Dev.
								6	2 Oper - 4 Dev
								1	Dev.
								1	Dev.
								2	Dev.
								4	Dev.
								1	Dev.
								1	Dev.
								6	Dev.
	1	1	1	1			1	44	12 Op - 29 Dev - 3 Ret
1	1	1	1	2	1	1	1	140	42 Op - 94 Dev - 4 Ret

## A 7.2 ALL LAUNCHERS DATABASE (by gross payload SSO 500 km orbit)

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
Japan	IHI Aerospace	SS-520	Oper.	2018	2 (1)	4	
USA	Cubecab	Cab-3A	Dev.	2022		5	0.25
Italy	Sidereus Space Dynamics	EOS	Dev.			10	0.105
USA	UP Aerospace	Spyder Orbital	Dev.	2021		10	0.7
Spain	Celestia Aerospace	Space Arrow CM	Dev.			16	0.2
Argentina	TLON Space	Aventura 1	Dev.			25	0.5
Australia	Eutropia Aerospace	ICI Launcher	Dev.			25	0.13
Iran		Qased	Oper.	2020	1	25	10
USA	VALT Enterprises	VALT	Dev.			25	1.7
USA	Vector Space Systems	Vector R	Oper.	2017	2	28	1.9
Iran		Safir	Oper.	2016	9 (4)	30	
USA	BlueShift Aerospace	Red Dwarf	Dev.	2022		30	1.25
USA	Interorbital Systems	Neptune N2	Dev.			30	0.5
Brazil	Acrux	Montenegro	Dev.	2022		40	0.6
South Korea	Perigee	Blue Whale	Dev.	2021		50	2
France	Venture Orbital Systems	Zéphir	Dev.	2023		70	
USA	Firehawk Aerospace	Firehawk-1	Dev.	2022		75	
Spain	Zero2infinity	Bloostar	Dev.			78	4
USA	Aevum	Ravn X	Dev.	2021		80	
Russia	Lin Industrial	Taymyr-7	Dev.			91.8	
China	Space Transportation	Tian Xing-1	Dev.			100	4
Iran	Agnikul	AgniBaan	Dev.			100	1.2
Japan	InterstellarTechnologies	Zero	Dev.	2022		100	0.44
Netherlands	Dawn Aerospace		Dev.			100	
Russia	Space Darts		Dev.			100	0.1
UK	Smallpark Space Syst.	Frost 1	Dev.	2023		100	1.3

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
		3 stages (solid)	2.9	0.5	Kagoshima (Japan)
50.0	Private				F-104 Air launch (KSC Florida)
10.5		SSTO (H2O2/Butane) 40 KN Reusable	2.07		
70.0	0.72 (NASA)	4 stages (solid)		0.4	New Mexico
12.5	Yes (Private)	Air launch + 3 stages (solid?)			MiG29-UB Air-launch
20.0		2 stages (Hybrid propulsion) First: 14 KN; Second: 1 KN	0.5	0.35	
5.0		Hybrid propulsion			
		3 stages (2 solid+1 liquid)	22		
68.0	Office Naval Research				
67.9	Yes (Private)	2 stages (LOx/Propylene) First: 3 LP-1 engines (81 KN) Second: 1 LP-2 engine (4.4 KN vac)	5		Mojave
		2 stages (Hydrazine/N2O4)	25		Semnan Space Center
41.7	0.3			0.6	Maine Spaceport
16.7	Yes (Private)	2 stages (2 modules each) (White fuming nitric acid & turpentine power)			Ocean (barge)
15.0	0.1				
40.0	13.9 (Private)	2 stages (LOx/LNG)	1.8	0.76	Whalers Way (Australia)
	0.9 Private Public (ESA, CNES)	2 stages (LOx/RP1) First: 6 engines Navier Second: 1 engine Navier		1	
	2 (Private)	Hybrid propulsion (2.2 KN; 22.2 KN planned) Acrylonitrile Butadiene Styrene/Aluminum			
51.3	13.83 (Private)	Balloon (30 km) 3 stages rocket (LOx/Methane) Reusable	4.9	2.9	El Arenosillo (Spain)
	4.9	Aircraft 2 stage rocket	25		
		3 stages (H2O2/RP1) First: 6 URB-1 (23.5 KN) Second: 1 DRM-1 (3.9 KN vac) Third: 1 URB-2 (0.98 KN)	15.6		
40.0	18 (Private)	First stage horizontal recovery			
12.0	3.6	3 stages (LOx/RP1)	13		
4.4	0.35 (Private)	3 stages(LOx/LNG)			Hokkaido (Japan)
	4.54	Spaceplane			
1.0	15				
13.0	0.15				

**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
UK	Space Launch Services	Prometheus-1	Dev.			100	
USA	ARCA	HAAS 2CA	Dev.	2022		100	1
USA	Exos Aerospace	Jaguar	Dev.	2023		100	5
USA	Spacedarts	X	Dev.			100	0.3
China	One Space	OS-M1	Oper.	2019	1 (1)	112	3.2
Argentina	LIA Aerospace	Procyon	Dev.	2026		120	3.8
Spain	Pangea Aerospace	MESO	Dev.			120	4.54
Canada	Reaction Dynamics	?	Dev.	2022		150	4.5
India	ISRO	ASLV	Ret.	1987	4 (2)	150	
India	Timewarp	Stardust	Dev.			150	
Japan	Space One	Space One	Dev.	2021		150	3.2
Russia	Laros	Laros RC-2	Dev.			150	3
Singapore	Equatorial Space Ind.	Volans	Dev.	2022		150	4.5
Sweden	Swedish Space Co	Rainbow	Dev.	2021		150	
UK	Orbex Space	Prime	Dev.	2022		150	
USA	Astra Space	Astra Rocket 3.2	Oper.	2020	2 (2)	150	3.75
USA	Stofiel Aerospace	BOREAS	Dev.			150	5
USA	Microcosm	Demi Sprite	Dev.			160	4.2
India	Bellatrix Aerospace	Chetak	Dev.	2024		162	2
France	ONERA	Altair	Dev.			162.8	5
China	Chinarocket Co (CALT)	Jie Long 1	Oper.	2019	1	170	6
China	China Rocket	Smart Dragon 1	Oper.	2019	1	200	6
China	LandSpace	Zhuque 1	Oper.	2018	1 (1)	200	

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
		3 stages (H2O2/RP1)			Andoya (Norway)
10.0		SSTO (H2O2/RP1) Aerospike	16		
50.0	9.1	First stage horizontal recovery			
3.0		Solid propellant			
28.6	116 ( Private) (HIT Robot Group, Others)	3 stages (solid) OS-M2 (+ 2 boosters) 420 kg SSO OS-M4 (+ 4 boosters) 471 kg SSO	21	1.2	Jiuquan (China North)
31.7		2 stages (H2O2/RP1)			Argentina
37.8	1.1 Private (The crowd angels)	2 stages (liquid) aerospike engines 30 - 300 kN First stage recovery			
30.0	1.15				Canso (Nova Scotia - Canada)
	Public	5 stages (solid)	39		Sriharikota island (India East)
		3 stages (2+ Kick; LOx/RP1) First: 9 engines (216 KN) Second: 1 engine (24 KN vac) Kick stage: Optional		1	
21.3	12.6 (Canon, Bank of Japan)	4 stages (3 solid+1 liquid)	23		
20.0		2 stages			
30.0	0.5	2 stages (LOx/Paraffin)			Sea platform
					Kiruna (Sweden) North Sea Mobile Platform? Kourou (French Guiana)?
	39.8 Private (Deimos, UK Sp. Agency) (Sunstone& Gründerf. Vent Cap) ESA: 7.45 M€ (2021)	2 stages (LOx/Propane) First: 6 engines (xxx KN) Second: 1 engine (yy KN vac) First stage recovery	18	1.3	Sutherland Spaceport (Scotland)
25.0	500 (Private)	2 stages (LOx/RP1) First: 5 Delphin engines (145 KN) Second: 1 Aether engine (2.96 KN vac)		1.3	Pacific Spaceport (Alaska) Kodiak Island
33.3	3.5 (Private)				Balloon based orbital launcher
26.3	26.25	Core stage (SR-M) + 6 identical pods that compose stages 1 and 2			
12.3	3 (Private)	2 stages(LOx/Methane)	12	2.0	
30.7	Private Public (ONERA,CNES)	EOLE Aircraft + 2 stage rocket (Hybrid) First: 7 engines (HTPB/H2O2) Second: 1 engines (HTPB/H2O2)	15	1.2	Kourou (French Guiana)
35.3	(Private)	4 stages (solid)	23	1.2	Jiuquan (China North)
30.0	Yes (Private)	4 stages (solid)	23.1	1.2	Jiuquan (China North)
	370 (Angels inves- tors)	3 stages (solid)	27	1.3	Jiuquan (China North)



**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
China	Link Space	New Line 1	Dev.	2021		200	4.5
France	Hybrid Propulsion	Mk2	Dev.	2024		200	4
Malaysia	IDXA	DNLV	Dev.	2022		200	4.5
North Korea	National Aerospace	Unha 3	Oper.	2012	5 (3)	200	
Philippines	Orbitx	Haribon SLS	Dev.			200	4.8
Taiwan	TiSpace	Hapith V	Dev.	2021		200	
USA	Rocket Lab	Electron	Oper.	2017	20 (3)	200	6.3
USA	Vector Space Systems	Vector R1	Dev.			200	
Australia	Gilmour Space	Eris-S	Dev.	2022		215	5.3
China	Expac (CASC)	Kuaizhou 1A	Oper.	2017	12 (1)	216	5.6
Norway	NAMMO	ENVOL	Dev.	2024		218	6.4
India	Skyroot	Vikram I	Dev.	2021		225	
China	Space Trek	Xingt-1 (XT-1)	Dev.	2021		240	
China	Galactic Energy	Ceres-1	Oper.	2020	1	248	4
China	i-Space Technology	Hyperbola 1 (SQX-1)	Oper.	2019	1	260	5
USA	Northrop Grumman	Pegasus XL	Oper.	1990	45 (5)	270	22
USA	Aerojet Rocketdyne	Spark/Super Strypi	Ret.	2015	1 (1)	275	12
China	Expac (CASC)	Kaituoze 2	Oper.	2017	1	283	
EU	Avio	Vega Light	Dev.			300	11.8
India	New Space India Ltd	SSLV	Dev.	2021		300	4.2
UK	Black Arrow	Black Arrow 2	Dev.			300	6.3
USA	Rocket Star		Dev.			300	6

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
22.5	20 (Private)	2 stages (LOx/RP1) First stage vertical recovery	33	1.8	Mangnai Quinghai
20.0		2 stages (LOx/solid fuel)	20	1.2	
22.5	Yes (Private)	3 stages (2 solid+1 LOx/RP1)			
	Public	3 stages (Hydrazine/N2O4)	91	1.3	Sohae
24.0	0.05				
		3 stages (solid)	23	1	Taiwan
31.5	300 (Private)	3 stages (2+ Kick; LOx/RP1) First: 9 Rutherford (162 KN) Second: 1 Rutherford mod (22 KN vac) Kick stage: Photon-Curie (120 N) First stage recovery (parachute/helicopter)	12.5	1.2	Mahia (NZ) Wallops (Virginia)
	Yes (Private)	2 stages (LOx/RP1) First: 4 Tanner SL engines (249 KN) Second: 1 Tanner engine (68.5 KN vac)		1.2	Wallops Island
24.7	17.6 (Private)	3 stages		1.2 - 1.5	North Queensland (Australia)
25.9	(Private)	4 stages (3 solid+1 liquid)	30	1.4	Jiuquan (China North) Taiyuan (China East)
29,5	Private	3 stages (Hybrid: H2O2/HTPB) First: 6 modules (630 KN) Second: 1 module (114 KN) Third: H2O2/RP-1 (6 KN)	34	1,5	Andoya (Norway)
	19 (Private)	3 stages (solid)			Sriharikota island (India East)
16.1	43 (Private)	3 stages (solid)	30	1.4	Jiuquan (China North)
19.2	275 (Private) (Matrix Partners China) (CDH Investments, Baidu)	4 stages (3 solid+1 liquid)	31		Wenchang (China South)
81.5	Yes	4 stages (3 solid+1 Hydrazine/N2O4)	23.1	1.3	L-1011 carrier aircraft
43.6		3 stages (solid)	30	1.3	Kuai island (Pacific)
		3 stages (solid)			
39.2	Private/Public (ESA)	3 stages (solid) First: Z40 SRM (1.304 KN) Second: Z9 SRM (317 KN) Third: Z2 SRM (new)	55	2	Kourou (French Guiana)
14.0		4 stages 3 solid + 1 liquid (kick stage)	120	2	Sriharikota island (India East)
21.0	0.1	2 stages (LOx/LNG) First: 5 engines (450 KN) Second: 1 engine (90 KN vac)		1.8	Seaborne launch vessel
20.0		SSTO RLV			

**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
USA	Virgin Orbit	LauncherOne	Dev.	2020	2 (1)	300	12
Iran		Safir 2 (Simorgh)	Oper.	2020	3 (3)	308	
UK	Skyrora	Skyrora-XL	Dev.	2023		315	12.6
USA	Phantom Space	Daytona E	Dev.	2023		320	
USA	Rocketcrafters	Intrepid 1	Dev.	2021		376	5.4
China	Chinarocket Co (CALT)	Long March 11	Oper.	2015	11	378	5
Israel	Israel Aerospace Ind.	Shavit 2	Oper.	2007	12 (3)	378	24
Germany	Hylmpulse	SL1	Dev.	2023		400	7.8
USA	Launcher Space	Rocket-1	Dev.	2025		400	10
India	Skyroot	Vikram II	Dev.	2022		410	
USA	SpaceX	Falcon 1	Ret.	2006	5 (3)	430	7
Japan	JAXA	Epsilon	Oper.	2013	4	450	39
Spain	PLD Space	Miura 5	Dev.	2024		450	8
China	China Rocket	Smart Dragon 2	Dev.	2021		500	
China	Deep Blue Aerospace	Nebula 1	Dev.	2021		500	
France	ArianeWorks	Morpho Micro	Dev.	2027		500	12
Russia	New Rocket Technol		Dev.			500	9
South Korea	INNOSPACE	Kuri	Dev.	2022		500	12.5
USA	United Frontiers	Discovery 2	Dormant			500	
USA	Vogue Aerospace	US1-LALV	Dev.			500	2
UK	Orbital Access	Orbital 500	Dev.	2023		518	15.5
India	Skyroot	Vikram III	Dev.	2023		580	
USA	Earth to Sky		Dev.	2021		600	4.5
USA	Firefly	Alpha ( $\alpha$ )	Dev.	2021		630	15
China	Expac (CASC)	Kaituoze 2A	Dev.			708	
Germany	Isar Aerospace	Spectrum	Dev.	2022		756	12

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
40.0	700 (Private)	2 stages (LOx/RP1) First: Newton 3 (327 KN) Second: Newton 4 (26.7 KN vac)	25.9	1.3	Bo747 carrier aircraft Mojave (California) Cornwall Airport (UK)
		3 stages (2 Hydrazine/N2O4+1solid)	86	2.5	Semnan Space Center
40.0	4.85 (Private)	3 stages (H2O2/RP1)	56	2.2	Sutherland (Scotland)
	0.9	2 stages (H2O2/RP1)			Cape Canaveral
14.4	10 (Florida State, DARPA)	2 stages	24.2	1.7	Cape Canaveral
13.2	Public	4 stages (solid)	58	2	Jiuquan (China North) Xichan (China SW)
63.5		4 stages (3 solid + 1 Hydrazine/N2O4)	32.9	1.4	Palmachim Airbase
19.5	3 Private 11 (Public?)	3 stages (LOx/Paraffin) First: 8 HyPLOx75 (648 KN) Second: 4 HyPLOx75 (400 KN vac) Third: 4 HyPLOx25 (110 KN)	36	2.2	SSC Esrange (Sweden) Norh Sea Mobile Platform? Kourou (French Guiana)?
25.0		2 stages (LOx/RP1)	33.4	1.7	Kennedy Space Centre Cape Canaveral
	19 (Private)	3 stages (2 solid+1 LOx/Methane)			
16.3	Yes	2 stages (LOx/RP1)	38.6	1.7	
86.7	Yes	4 stages (3 solid + 1 Hydrazine/N2O4)	95.4	2.5	Uchinoura (Japan)
17,8	32 (GMV, Caixa Bank) (CDTI, JME Ventures)	2 stages (LOx/RP1) First: 5 Teprel C (525 KN) Second: 1 Teprel C (45 KN vac) Kick stage: Optional First stage recovery (parachute)	32	1,8	Kourou (French Guiana)
	Yes (Private)	4 stages (solid)	60	2	Jiuquan (China North)
	14 (Private)	2 stages (LOx/RP1) First stage vertical recovery			
24.0		2 Stages (LOx/CH4) First reusable (3 Prometheus 2.940 KN) Second stage: Not yet defined			Kourou (French Guiana)
18.0		2 stages			
25.0	1.5	3 stages (hybrid)	200		
					Cape Canaveral
4.0	0.1				
29.9	0.2 (Private)	Air-launch (MD-11): H=13.000 m First stage: Reusable spaceplane (H=80 km) Second stage: expendable			Prestwick (Scotland)
	19 (Private)	Vikram II+6 solid boosters			
7.5	5.25				
23.8	23.16	2 stages (LOx/RP1)	54	2	Vandenberg (California)
		3 stages (solid) + 2 solid boosters			
15.9	110 (Private)	2 (LOx/Light Hydrocarbon) First: 9 Aquila engines (675 KN) Second: 1 Aquila engine (94 KN vac)	65	1.8 - 2.5	Norh Sea Platform Kourou (French Guiana)?

**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
USA	ABL Space Systems	RS 1	Dev.	2021		875	12
USA	Relativity Space	Terran 1	Dev.	2021		900	12
South Africa	Marcom	Cheetah	Dev.			1 000	8
China	Expace (CASC)	Kuaizhou 11	Dev.	2020	1 (1)	1 080	10
USA	Northrop Grumman	Minotaur 4	Oper.	2010	6	1 090	48
China	i-Space	Hyperbola 2	Dev.	2021		1 100	
USA	Eclipse Orbital	Totalitas	Dev.	2022		1 100	10
China	Chinarocket Co (CALT)	Long March 6	Oper.	2015	5	1 220	
Russia	Krunichev	Rockot	Oper.	1994	34 (3)	1 240	44
USA	Interorbital Systems	Neptune N9	Dev.			1 250	
Germany	Rocket Factory	RFAOne	Dev.	2022		1 275	
China	Chinarocket Co (CALT)	Long March 2D	Oper.	1992	52 (1)	1 336	26
EU	Avio	Vega	Oper.	2012	17 (2)	1 435	42
China	China Rocket	Smart Dragon 3	Dev.	2022		1 500	
France	ArianeWorks	Morpho Mini	Dev			1 800	24
India	ISRO	PSLV	Oper.	1994	52 (3)	1 814	28
China	LandSpace	Zhuque 2	Dev.	2021		2 000	
China	Chinarocket Co (CALT)	Long March 2C	Oper.	1982	59 (2)	2 159	27
USA	United Launch Alliance	Delta 2 (7420)	Oper.			2 200	
China	Galactic Energy	Pallas 1	Dev.	2022		2 260	28
China	Chinarocket Co (CALT)	Long March 4B	Oper.	1999	40 (1)	2 359	31

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
13.7	49	2 stages (LOx/RP1)			Camdem County
13.3	685 (Private)	2 stages (LOx/LNG) First: 9 Aeon 1 engines (1.016 KN) Second: 1 Aeon 1 engine (132.5 KN vac)		3	Cape Canaveral Vandenberg
8.0					
9.3	370 (Private)	4 stages (3 solid+1 liquid)	78	2.2	Jiuquan (China North) Taiyuan (China East)
44.0	Yes (Private)	4 stages (solid)	86	2.3	Vandenberg
	Yes (Private)	2 stages (LOx/Methane) First stage vertical recovery	90	3.35	Jiuquan (China North)
9.1	Yes (Private)	2 stages First: 685 KN (reusable) Second: xx KN vac 2 Boosters (reusable)	65	2.1	Ocean vessel platform
	Public	3 stages (LOx/RP1)	217	2.6	Taiyuan (China East)
35.5	Private/Public	3 stages (Hydrazine/N2O4)	107	2.5	Plesetsk
	Yes (Private)	2 stages (6 modules each) (White fuming nitric acid & turpentine power)			Ocean (barge)
	17.5 Private (OHB: 46.4 %)	3 stages (LOx/RP1) First: 8 ORSC engines (<800KN) Second: 1 ORSC engine (100 KN vac) Kickstage: 1 engine (1.5 KN vac) (?)		2.1	Andoya (Norway) Kourou (French Guiana)?
19.5	Public	3 stages (Hydrazine/N2O4)	302	3.35	Jiuquan (China North) Taiyuan (China East)
29.3	Private/Public (ESA)	4 stages (3 solid+1 Hydrazine/N2O4) First: P80 (3.040 KN) Second: Zefiro 33 (1.200 KN) Third: Zefiro 9 (213 KN) Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	137	3	Kourou (French Guiana)
	Yes (Private)	4 stages (solid)	116	2.6	Jiuquan (China North)
13.3		2 Stages (LOx/CH4) First (7 Prometheus 6.680 KN) Second stage: Not yet defined			Kourou (French Guiana)
15.4	Yes	4 stages (3 solid+1 Hydrazine/N2O4)	320	2.8	Sriharikota island (India East)
	361.3 (Private)	2 stages (LOx/Paraffin) First: 4 TQ-12 engines (2.626 KN) Second: ( KN vac) First stage vertical recovery	216	3.4	Jiuquan (China North)
12.5	Public	3 stages (Hydrazine/N2O4)	233	3.4	Jiuquan (China North) Taiyuan (China East) Xichan (China SW)
	Private	2 stages (1 LOx/RP1+1 N2O4/Hydrazine) + 4 boosters solid	162	3.0	Cape Canaveral Vandenberg
12.4	43 (Private)	2 stages (LOx/Kerosene) First stage vertical recovery		4	Jiuquan (China North)
13.1	Public	3 stages (Hydrazine/N2O4)	249	3.4	Jiuquan (China North) Taiyuan (China East)

**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
EU	Avio	Vega C	Dev.	2022		2 390	42
EU	Avio	Vega E	Dev.	2024		2 700	
China	Chinarocket Co (CALT)	Long March 4C	Oper.	2006	29 (2)	2 878	
USA	Interorbital Systems	Neptune N36	Dev.			3 200	
USA	United Launch Alliance	Delta 2 (7920)	Oper.			3 450	137
USA	Northrop Grumman	Antares	Oper.	2019	9	3 600	80
Russia	Progress Rocket SC	Soyouz 2	Oper.	2004	85 (5)	4 400	80
Canada	Maritime Launch Services		Dev.			5 000	45
China	Chinarocket Co (CALT)	Long March 8	Oper.	2020	1	5 140	
Canada	Space Engine Systems		Dev.			5 500	
USA	Firefly	Beta	Dev.			5 800	
USA	Rocket Lab	Neutron	Dev.	2024		6 400	
EU	Ariane Group	Ariane 62	Dev.	2022		6 450	88.2
China	Chinarocket Co (CALT)	Long March 3B/E	Oper.	1996	89 (4)	7 299	74
China	Chinarocket Co (CALT)	Long March 7A	Oper.	2020	3	8 738	
USA	United Launch Alliance	Delta 4M 5-2	Oper.	2012	13 (1)	10 500	164
USA	SpaceX	Falcon 9	Oper.	2010	101 (3)	13 150	56
USA	United Launch Alliance	Atlas 5	Oper.	2002	87 (1)	13 929	153
USA	Relativity Space	Terran R	Dev.	2024		14 400	

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
17.6	Private/Public (ESA)	4 stages (3 solid+1 N2O4/Hydrazine) First: P120 C (4.323 KN) Second: Zefiro 40 (1.304 KN) Third: Zefiro 9 (317 KN) Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	210	3.3	Kourou (French Guiana)
	Private/Public (ESA)	3 stages (2 solid+1 LOx/Methane) First: P120 C (4.323 KN) Second: Zefiro 40 (1.304 KN) Third: M10 (LOx/Methane) (98 KN)			Kourou (French Guiana)
	Public	3 stages (Hydrazine/N2O4)	249	3.4	Jiuquan (China North) Taiyuan (China East) Xichan (China SW)
	Yes (Private)	2 stages (36 modules each) (White fuming nitric acid & turpentine power)			Ocean (barge)
39.7	Private	2 stages (LOx/RP1+1 N2O4/Hydrazine) + 9 boosters solid	228	3.0	Cape Canaveral Vandenberg
22.2	Private	3 stages (LOx/RP1+1 solid+1 N2O4/Hydrazine)	298	3.9	Cape Canaveral
18.2	Private/Public	3 stages (LOx/RP1)	308	4.1	Baikonur/Plesetsk Kourou (French Guiana)
9.0					
	Public	2 stages (1 LOx/RP1 + 1 LOx/LH2) + 2 boosters (LOx/Kerosene) First stage recovery	357	3.4	Jiuquan (China North) Wengchan
	22	Space plane SSTO Reusable			
		2 stages (LOx/RP1) First: 5 Reaver 2 engines (4.261 KN) Second: 1 Reaver 1 Vac (194 KN)		4.7	
		2 stages (LOx/RP1) First stage reusable		4.5	Ocean platform
13.7	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	530	5.4	Kourou (French Guiana)
10.1	Public	3 stages (2 Hydrazine/N2O4+ 1 LOx/LH2) + 4 boosters	459	3.35	
	Public	3 stages (2 LOx/RP1+ 1 LOx/LH2) + 4 boosters (LOx/RP1)	573	3.35	Wengchan
15.6	Private	2 stages (1 CBC LOx/LH2+ 1 LOx/LH2) + 2 boosters solid	332	5	Cape Canaveral Vandenberg
4.3	5.870 (Private)	2 Stages (LOx/RP1) First: 9 Merlin D engines (7.605 KN) Second: 1 Merlin D engine (862 KN) First stage reusable	549	5.2	Vandenberg (SSO) KSC (GTO)
11.0	Private	2 stages (1 LOx/RP1+1 LOx/LH2) + 0 - 5 boosters solid	590	4.2	Cape Canaveral
	650 (Private)	2 stages (LOx/Methane) First: 7 Aeon R engines (7 x 1.342 KN) Second: 1 Aeon R engine (1.745 KN vac) Fully reusable (2 stages + fairing)			Cape Canaveral Vandenberg



**All launchers database (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
EU	Ariane Group	Ariane 64	Dev.	2022		14 900	135.3
China	Chinarocket Co (CALT)	Long March 5B	Oper.	2016	7 (1)	15 420	182
EU	Ariane Group	Ariane 5	Oper.	1996	109 (5)	15 700	170
USA	United Launch Alliance	Delta 4 Heavy	Oper.	2004	12 (1)	22 850	300

Table 16: All launchers database (by gross payload SSO 500 km orbit).

**A 7.3 ALL LAUNCHERS DATABASE (by country)****Europe**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
EU	Avio	Vega Light	Dev.			300	11.8
EU	Avio	Vega	Oper.	2012	17 (2)	1 435	42
EU	Avio	Vega C	Dev.	2021		2 390	42
EU	Avio	Vega E	Dev.	2024		2 700	
EU	Ariane Group	Ariane 62	Dev.	2021		6 450	88.2
EU	Ariane Group	Ariane 64	Dev.	2021		14 900	135.3
EU	Ariane Group	Ariane 5	Oper.	1996	109 (5)	15 700	170
France	Venture Orbital Systems	Zéphir	Dev.	2023		70	
France	ONERA	Altair	Dev.			162.8	5

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
9.1	Private/Public (ESA)	2 stages (LOx/LH2) + 4 solid boosters	860	5.4	Kourou (French Guiana)
11.8	Public	3 stages (2 LOx/LH2 + 1 Hydrazine/N2O4) + 4 boosters (LOx/RP1)	838	3.35	Wengchan
10.8	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	780	5.4	Kourou (French Guiana)
13.1	Private	2 stages (1 CBC LOx/LH2 + 1 LOx/LH2) + 2 CBC (LOx/LH2)	733	5	Cape Canaveral Vandenberg

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
39.2	Private/Public (ESA)	3 stages (solid)-First: Z40 SRM (1.304 KN)-Second: Z9 SRM (317 KN)-Third: Z2 SRM (new)	55	2	Kourou (French Guiana)
29.3	Private/Public (ESA)	4 stages (3 solid+1 Hydrazine/N2O4)-First: P80 (3.040 KN)-Second: Zefiro 33 (1.200 KN)-Third: Zefiro 9 (213 KN)-Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	137	3	Kourou (French Guiana)
17.6	Private/Public (ESA)	4 stages (3 solid+1 N2O4/Hydrazine)-First: P120 C (4.323 KN)-Second: Zefiro 40 (1.304 KN)-Third: Zefiro 9 (317 KN)-Fourth: AVUM (Hydrazine/N2O4) (2.45 KN)	210	3.3	Kourou (French Guiana)
	Private/Public (ESA)	3 stages (2 solid+1 LOx/Methane)-First: P120 C (4.323 KN)-Second: Zefiro 40 (1.304 KN)-Third: M10 (LOx/Methane) (98 KN)			Kourou (French Guiana)
13.7	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	530	5.4	Kourou (French Guiana)
9.1	Private/Public (ESA)	2 stages (LOx/LH2) + 4 solid boosters	860	5.4	Kourou (French Guiana)
10.8	Private/Public (ESA)	2 stages (LOx/LH2) + 2 solid boosters	780	5.4	Kourou (French Guiana)
	0.9 Private-Public (ESA, CNES)	2 stages (LOx/RP1)-First: 6 engines Navier-Second: 1 engine Navier		1	
30.7	Private-Public (ONERA, CNES)	EOLE Aircraft + 2 stage rocket (Hybrid)-First: 7 engines (HTPB/H2O2)-Second: 1 engines (HTPB/H2O2)	15	1.2	Kourou (French Guiana)

**Europe (cont.)**

Country	Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
France	Hybrid Propulsion	Mk2	Dev.	2024		200	4
France	ArianeWorks	Morpho Micro	Dev	2027		500	12
France	ArianeWorks	Morpho Mini	Dev			1 800	24
Germany	Hylmpulse	SL1	Dev.	2023		400	7.8
Germany	Isar Aerospace	Spectrum	Dev.	2022		756	12
Germany	Rocket Factory	RFAOne	Dev.	2022		1 275	
Italy	Sidereus Space Dynamics	EOS	Dev.			10	0.105
Norway	NAMMO	ENVOL	Dev.	2024		218	6.4
Spain	Celestia Aerospace	Space Arrow CM	Dev.			16	0.2
Spain	Zero2infinity	Bloostar	Dev.			78	4
Spain	Pangea Aerospace	MESO	Dev.			120	4.54
Spain	PLD Space	Miura 5	Dev.	2024		450	8
Sweden	Swedish Space Co	Rainbow	Dev.	2021		150	
UK	Smallpark Space Syst.	Frost 1	Dev.	2023		100	1.3
UK	Space Launch Services	Prometheus-1	Dev.			100	
UK	Orbex Space	Prime	Dev.	2022		150	
UK	Black Arrow	Black Arrow 2	Dev.			300	6.3
UK	Skyrora	Skyrora-XL	Dev.	2023		315	12.6
UK	Orbital Access	Orbital 500	Dev.	2023		518	15.5

Table 17: European launchers.

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
20.0		2 stages (LOx/solid fuel)	20	1.2	
24.0		2 Stages (LOx/CH4)-First reusable (3 Prometheus 2.940 KN)-Second stage: Not yet defined			Kourou (French Guiana)
13.3		2 Stages (LOx/CH4)-First (7 Prometheus 6.680 KN)-Second stage: Not yet defined			Kourou (French Guiana)
19.5	3 Private-11 (Public?)	3 stages (LOx/Paraffin)-First: 8 HyPLOx75 (648 KN)-Second: 4 HyPLOx75 (400 KN vac)-Third: 4 HyPLOx25 (110 KN)	36	2.2	SSC Esrange (Sweden)-Norh Sea Mobile Platform?-Kourou (French Guiana)?
15.9	110 (Private)	2 (LOx/Light Hydrocarbon)-First: 9 Aquila engines (675 KN)-Second: 1 Aquila engine (94 KN vac)	65	1.8 - 2.5	North Sea Platform-Kourou (French Guiana)?
	17.5 Private-(OHB: 46.4 %)	3 stages (LOx/RP1)-First: 8 ORSC engines (<800KN)-Second: 1 ORSC engine (100 KN vac)-Kickstage: 1 engine (1.5 KN vac) (?)		2.1	Andoya (Norway)-Kourou (French Guiana)?
10.5		SSTO (H2O2/Butane) 40 KN-Reusable	2.07		
29.5	Private	3 stages (Hybrid: H2O2/HTPB) First: 6 modules (630 KN) Second: 1 module (114 KN) Third: H2O2/RP-1 (6 KN)	34	1,5	Andoya (Norway)
12.5	Yes (Private)	Air launch + 3 stages (solid?)			MiG29-UB Air-launch
51.3	13.83 (Private)	Balloon (30 km)-3 stages rocket (LOx/Methane)-Reusable	4.9	2.9	El Arenosillo (Spain)
37.8	1.1 Private-(The crowd angels)	2 stages (liquid)-aerospike engines 30 - 300 kN-First stage recovery			
26.7	32 (GMV, Caixa Bank)-(CDTI, JME Ventures)	2 stages (LOx/RP1)-First: 5 Teprel C (408 KN)-Second: 1 Teprel C (65 KN vac)-Kick stage: Optional-First stage recovery (parachute)	32	1.8	Kourou (French Guiana)
					Kiruna (Sweden)-Norh Sea Mobile Platform?-Kourou (French Guiana)?
13.0	0.15				
		3 stages (H2O2/RP1)			Andoya (Norway)
	39.8 Private-(Deimos, UK Space Agency)-(Sunstone&Gründerf. Vent Cap)-ESA: 7.45 M€ (2021)	2 stages (LOx/Propane)-First: 6 engines (xxx KN)-Second: 1 engine (yy KN vac)-First stage recovery	18	1.3	Sutherland Spaceport-(Scotland)
21.0	0.1	2 stages (LOx/LNG)-First: 5 engines (450 KN)-Second: 1 engine (90 KN vac)		1.8	Seaborne launch vessel
40.0	4.85 (Private)	3 stages (H2O2/RP1)	56	2.2	Sutherland (Scotland)
29.9	0.2 (Private)	Air-launch (MD-11): H=13.000 m-First: Reusable spaceplane (H=80 km)-Second stage: expendable			Prestwick (Scotland)

## USA

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
Cubecab	Cab-3A	Dev.	2022		5	0.25
UP Aerospace	Spyder Orbital	Dev.	2021		10	0.7
VALT Enterprises	VALT	Dev.			25	1.7
Vector Space Systems	Vector R	Oper.	2017	2	28	1.9
BlueShift Aerospace	Red Dwarf	Dev.	2022		30	1.25
Interorbital Systems	Neptune N2	Dev.			30	0.5
Firehawk Aerospace	Firehawk-1	Dev.	2022		75	
Aevum	Ravn X	Dev.	2021		80	
ARCA	HAAS 2CA	Dev.	2022		100	1
Exos Aerospace	Jaguar	Dev.	2023		100	5
Spacedarts	X	Dev.			100	0.3
Astra Space	Astra Rocket 3.2	Oper.	2020	2 (2)	150	3.75
Stofiel Aerospace	BOREAS	Dev.			150	5
Microcosm	Demi Sprite	Dev.			160	4.2
Rocket Lab	Electron	Oper.	2017	20 (3)	200	6.3
Vector Space Systems	Vector R1	Dev.			200	
Northrop Grumman	Pegasus XL	Oper.	1990	45 (5)	270	22
Aerojet Rocketdyne	Spark/Super Strypi	Ret.	2015	1 (1)	275	12
Rocket Star		Dev.			300	6
Virgin Orbit	LauncherOne	Dev.	2020	2 (1)	300	12
Phantom Space	Daytona E	Dev.	2023		320	
Rocketcrafters	Intrepid 1	Dev.	2021		376	5.4
Launcher Space	Rocket-1	Dev.	2025		400	10
SpaceX	Falcon 1	Ret.	2006	5 (3)	430	7
United Frontiers	Discovery 2	Dormant			500	
Vogue Aerospace	US1-LALV	Dev.			500	2
Earth to Sky		Dev.	2021		600	4.5
Firefly	Alpha (α)	Dev.	2021		630	15
ABL Space Systems	RS 1	Dev.	2021		875	12
Relativity Space	Terran 1	Dev.	2021		900	12
Northrop Grumman	Minotaur 4	Oper.	2010	6	1 090	48
Eclipse Orbital	Totalitas	Dev.	2022		1 100	10

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
50.0	Private				F-104 Air launch (KSC Florida)
70.0	0.72 (NASA)	4 stages (solid)		0.4	New Mexico
68.0	Office Naval Research				
67.9	Yes (Private)	2 stages (LOx/Propylene)-First: 3 LP-1 engines (81 KN)-Second: 1 LP-2 engine (4.4 KN vac)	5		Mojave
41.7	0.3			0.6	Maine Spaceport
16.7	Yes (Private)	2 stages (2 modules each)-(White fuming nitric acid & turpentine power)			Ocean (barge)
	2 (Private)	Hybrid propulsion (2.2 KN; 22.2 KN planned)-Acrylonitrile Butadiene Styrene/Aluminum			
	4.9	Aircraft. 2 stage rocket	25		
10.0		SSTO (H2O2/RP1) Aerospike	16		
50.0	9.1	First stage horizontal recovery			
3.0		Solid propellant			
25.0	500 (Private)	2 stages (LOx/RP1)-First: 5 Delphin engines (145 KN)-Second: 1 Aether engine (2.96 KN vac)		1.3	Pacific Spaceport (Alaska)-Kodiak Island
33.3	3.5 (Private)				Balloon based orbital launcher
26.3	26.25	Core stage (SR-M) + 6 identical pods-that compose stages 1 and 2			
31.5	300 (Private)	3 stages (2+ Kick; LOx/RP1)-First: 9 Rutherford (162 KN)-Second: 1 Rutherford mod (22 KN vac)-Kick stage: Photon-Curie (120 N)-First stage recovery (parachute/helicopter)	12.5	1.2	Mahia (NZ)-Wallops (Virginia)
	Yes (Private)	2 stages (LOx/RP1)-First: 4 Tanner SL engines (249 KN)-Second: 1 Tanner engine (68.5 KN vac)		1.2	Wallops Island
81.5	Yes	4 stages (3 solid+1 Hydrazine/N2O4)	23.1	1.3	L-1011 carrier aircraft
43.6		3 stages (solid)	30	1.3	Kuai island (Pacific)
20.0		SSTO RLV			
40.0	700 (Private)	2 stages (LOx/RP1)-First: Newton 3 (327 KN)-Second: Newton 4 (26.7 KN vac)	25.9	1.3	Bo747 carrier aircraft-Mojave (California)-Cornwall Airport (UK)
	0.9	2 stages (H2O2/RP1)			Cape Canaveral
14.4	10 (Florida State, DARPA)	2 stages	24.2	1.7	Cape Canaveral
25.0		2 stages (LOx/RP1)	33.4	1.7	Kennedy Space Centre-Cape Canaveral
16.3	Yes	2 stages (LOx/RP1)	38.6	1.7	Cape Canaveral
					Cape Canaveral
4.0	0.1				
7.5	5.25				
23.8	23.16	2 stages (LOx/RP1)	54	2	Vandenberg (California)
13.7	49	2 stages (LOx/RP1)			Camdem County
13.3	685 (Private)	2 stages (LOx/LNG)-First: 9 Aeon 1 engines (1.016 KN)-Second: 1 Aeon 1 engine (132.5 KN vac)		3	Cape Canaveral Vandenberg
44.0	Yes (Private)	4 stages (solid)	86	2.3	Vandenberg
9.1	Yes (Private)	2 stages-First: 685 KN (reusable)-Second: xx KN vac-2 Boosters (reusable)	65	2.1	Ocean vessel platform

**USA (cont.)**

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
Interorbital Systems	Neptune N9	Dev.			1 250	
United Launch Alliance	Delta 2 (7420)	Oper.			2 200	
Interorbital Systems	Neptune N36	Dev.			3 200	
United Launch Alliance	Delta 2 (7920)	Oper.			3 450	137
Northrop Grumman	Antares	Oper.	2019	9	3 600	80
Firefly	Beta	Dev.			5 800	
Rocket Lab	Neutron	Dev.	2024		6 400	
United Launch Alliance	Delta 4M 5-2	Oper.	2012	13 (1)	10 500	164
SpaceX	Falcon 9	Oper.	2010	101 (3)	13 150	56
United Launch Alliance	Atlas 5	Oper.	2002	87 (1)	13 929	153
Relativity Space	Terran R	Dev.	2024		14 400	
United Launch Alliance	Delta 4 Heavy	Oper.	2004	12 (1)	22 850	300

Table 18: US launchers.

**China**

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
Space Transportation	Tian Xing-1	Dev.			100	4
One Space	OS-M1	Oper.	2019	1 (1)	112	3.2
Chinarocket Co (CALT)	Jie Long 1	Oper.	2019	1	170	6
China Rocket	Smart Dragon 1	Oper.	2019	1	200	6
LandSpace	Zhuque 1	Oper.	2018	1 (1)	200	
Link Space	New Line 1	Dev.	2021		200	4.5
Expac (CASC)	Kuaizhou 1A	Oper.	2017	12 (1)	216	5.6

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
	Yes (Private)	2 stages (6 modules each)-(White fuming nitric acid & turpentine power)			Ocean (barge)
	Private	2 stages (1 LOx/RP1+1 N2O4/Hydrazine)-> 4 boosters solid	162	3.0	Cape Canaveral Vandenberg
	Yes (Private)	2 stages (36 modules each)- (White fuming nitric acid & turpentine power)			Ocean (barge)
39.7	Private	2 stages (LOx/RP1+1 N2O4/Hydrazine)-> 9 boosters solid	228	3.0	Cape Canaveral-Vandenberg
22.2	Private	3 stages (LOx/RP1+1 solid+1 N2O4/Hydrazine)	298	3.9	Cape Canaveral
		2 stages (LOx/RP1)-First: 5 Reaver 2 engines (4.261 KN)-Second: 1 Reaver 1 Vac (194 KN)		4.7	
		2 stages (LOx/RP1). First stage reusable		4.5	Ocean platform
15.6	Private	2 stages (1 CBC LOx/LH2+ 1 LOx/LH2)- + 2 boosters solid	332	5	Cape Canaveral Vandenberg
4.3	5.870 (Private)	2 Stages (LOx/RP1)-First: 9 Merlin D engines (7.605 KN)-Second: 1 Merlin D engine (862 KN)-First stage reusable	549	5.2	Vandenberg (SSO)-KSC (GTO)
11.0	Private	2 stages (1 LOx/RP1+1 LOx/LH2)+ 0 - 5 boosters solid	590	4.2	Cape Canaveral
	650 (Private)	2 stages (LOx/Methane)-First: 7 Aeon R engines (7 x 1.342 KN)-Second: 1 Aeon R engine (1.745 KN vac)-Fully reusable (2 stages + fairing)			Cape Canaveral Vandenberg
13.1	Private	2 stages (1 CBC LOx/LH2 + 1 LOx/LH2)-> 2 CBC (LOx/LH2)	733	5	Cape Canaveral Vandenberg

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
40.0	18 (Private)	First stage horizontal recovery			
28.6	116 ( Private)-(HIT Robot Group, Others)	3 stages (solid)-OS-M2 (+ 2 boosters) 420 kg SSO-OS-M4 (+ 4 boosters) 471 kg SSO	21	1.2	Jiuquan (China North)
35.3	(Private)	4 stages (solid)	23	1.2	Jiuquan (China North)
30.0	Yes (Private)	4 stages (solid)	23.1	1.2	Jiuquan (China North)
	370 (Angels investors)	3 stages (solid)	27	1.3	Jiuquan (China North)
22.5	20 (Private)	2 stages (LOx/RP1)-First stage vertical recovery	33	1.8	Mangnai-Quinghai
25.9	(Private)	4 stages (3 solid+1 liquid)	30	1.4	Jiuquan (China North) Taiyuan (China East)



**China (cont.)**

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg)-SSO 500 km	Price (M\$)
Space Trek	Xingtu-1 (XT-1)	Dev.	2021		240	
Galactic Energy	Ceres-1	Oper.	2020	1	248	4
i-Space Technology	Hyperbola 1 (SQX-1)	Oper.	2019	1	260	5
Expace (CASC)	Kaituoze 2	Oper.	2017	1	283	
Chinarocket Co (CALT)	Long March 11	Oper.	2015	11	378	5
China Rocket	Smart Dragon 2	Dev.	2021		500	
Deep Blue Aerospace	Nebula 1	Dev.	2021		500	
Expace (CASC)	Kaituoze 2A	Dev.			708	
Expace (CASC)	Kuaizhou 11	Dev.	2020	1 (1)	1 080	10
i-Space	Hyperbola 2	Dev.	2021		1 100	
Chinarocket Co (CALT)	Long March 6	Oper.	2015	5	1 220	
Chinarocket Co (CALT)	Long March 2D	Oper.	1992	52 (1)	1 336	26
China Rocket	Smart Dragon 3	Dev.	2022		1 500	
LandSpace	Zhuque 2	Dev.	2021		2 000	
Chinarocket Co (CALT)	Long March 2C	Oper.	1982	59 (2)	2 159	27
Galactic Energy	Pallas 1	Dev.	2022		2 260	28
Chinarocket Co (CALT)	Long March 4B	Oper.	1999	40 (1)	2 359	31
Chinarocket Co (CALT)	Long March 4C	Oper.	2006	29 (2)	2 878	
Chinarocket Co (CALT)	Long March 8	Oper.	2020	1	5 140	
Chinarocket Co (CALT)	Long March 3B/E	Oper.	1996	89 (4)	7 299	74
Chinarocket Co (CALT)	Long March 7A	Oper.	2020	3	8 738	
Chinarocket Co (CALT)	Long March 5B	Oper.	2016	7 (1)	15 420	182

Table 19: Chinese launchers.

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
16.1	43 (Private)	3 stages (solid)	30	1.4	Jiuquan (China North)
19.2	275 (Private)-(Matrix Partners China)-(CDH Investments, Baidu)	4 stages (3 solid+1 liquid)	31		Wenchang (China South)
		3 stages (solid)			
13.2	Public	4 stages (solid)	58	2	Jiuquan (China North)-Xi-chan (China SW)
	Yes (Private)	4 stages (solid)	60	2	Jiuquan (China North)
	14 (Private)	2 stages (LOx/RP1)-First stage vertical recovery			
		3 stages (solid) + 2 solid boosters			
9.3	370 (Private)	4 stages (3 solid+1 liquid)	78	2.2	Jiuquan (China North)-Taiyuan (China East)
	Yes (Private)	2 stages (LOx/Methane)-First stage vertical recovery	90	3.35	Jiuquan (China North)
	Public	3 stages (LOx/RP1)	217	2.6	Taiyuan (China East)
19.5	Public	3 stages (Hydrazine/N2O4)	302	3.35	Jiuquan (China North)-Taiyuan (China East)
	Yes (Private)	4 stages (solid)	116	2.6	Jiuquan (China North)
	361.3 (Private)	2 stages (LOx/Paraffin)-First: 4 TQ-12 engines (2.626 KN)-Second: ( KN vac)-First stage vertical recovery	216	3.4	Jiuquan (China North)
12.5	Public	3 stages (Hydrazine/N2O4)	233	3.4	Jiuquan (China North)-Taiyuan (China East)-Xi-chan (China SW)
12.4	43 (Private)	2 stages (LOx/Kerosene)-First stage vertical recovery		4	Jiuquan (China North)
13.1	Public	3 stages (Hydrazine/N2O4)	249	3.4	Jiuquan (China North)-Taiyuan (China East)
	Public	3 stages (Hydrazine/N2O4)	249	3.4	Jiuquan (China North)-Taiyuan (China East)-Xi-chan (China SW)
	Public	2 stages (1 LOx/RP1 + 1 LOx/LH2)-+ 2 boosters (LOx/Kerosene)-First stage recovery	357	3.4	Jiuquan (China North)-Wengchan
10.1	Public	3 stages (2 Hydrazine/N2O4+ 1 LOx/LH2)-+ 4 boosters	459	3.35	
	Public	3 stages (2 LOx/RP1+ 1 LOx/LH2)-+ 4 boosters (LOx/RP1)	573	3.35	Wengchan
11.8	Public	3 stages (2 LOx/LH2 + 1 Hydrazine/N2O4)-+ 4 boosters (LOx/RP1)	838	3.35	Wengchan

**Russia**

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
Lin Industrial	Taymyr-7	Dev.			91.8	
Space Darts		Dev.			100	0.1
Laros	Laros RC-2	Dev.			150	3
New Rocket Technol		Dev.			500	9
Krunichev	Rocket	Oper.	1994	34 (3)	1 240	44
Progress Rocket SC	Soyouz 2	Oper.	2004	85 (5)	4 400	80
i-Space	Hyperbola 2	Dev.	2021		1 100	

Table 20: Russian launchers.

**India**

Company	Launcher	Status	First flight	Launches (Failures)	Payload (kg) SSO 500 km	Price (M\$)
ISRO	ASLV	Ret.	1987	4 (2)	150	
Timewarp	Stardust	Dev.			150	
Bellatrix Aerospace	Chetak	Dev.	2024		162	2
Skyroot	Vikram I	Dev.	2021		225	
New Space India Ltd	SSLV	Dev.	2021		300	4.2
Skyroot	Vikram II	Dev.	2022		410	
Skyroot	Vikram III	Dev.	2023		580	
ISRO	PSLV	Oper.	1994	52 (3)	1 814	28

Table 21: Indian launchers.

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
		3 stages (H2O2/RP1)-First: 6 URB-1 (23.5 KN)-Second: 1 DRM-1 (3.9 KN vac)-Third: 1 URB-2 (0.98 KN)	15.6		
1.0	15				
20.0		2 stages			
18.0		2 stages			
35.5	Private/Public	3 stages (Hydrazine/N2O4)	107	2.5	Plesetsk
18.2	Private/Public	3 stages (LOx/RP1)	308	4.1	Baikonur/Plesetsk-Kourou (French Guiana)
	Yes (Private)	2 stages (LOx/Methane)-First stage vertical recovery	90	3.35	Jiuquan (China North)

Price (k\$/kg)	Funding (M\$)	Staging	Mass (tons)	Fairing Ø (m)	Launch site
	Public	5 stages (solid)	39		Sriharikota island (India East)
		3 stages (2+ Kick; LOx/RP1)-First: 9 engines (216 KN)-Second: 1 engine (24 KN vac)-Kick stage: Optional		1	
12.3	3 (Private)	2 stages(LOx/Methane)	12	2.0	
	19 (Private)	3 stages (solid)			Sriharikota island (India East)
14.0		4 stages-3 solid + 1 liquid (kick stage)	120	2	Sriharikota island (India East)
	19 (Private)	3 stages (2 solid+1 LOx/Methane)			
	19 (Private)	Vikram II+6 solid boosters			
15.4	Yes	4 stages (3 solid+1 Hydrazine/N2O4)	320	2.8	Sriharikota island (India East)

#### A 7.4 ALL LAUNCHERS DATABASE BY PAYLOAD AND PROPELLANT USED

All launchers	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450
Solid	4	1	3	7	3	6		1	2
LOx/RP1		2	2	4		2	1	1	2
LOx/Methane	1	2		1		1			
Hydrazine/N2O4	1			1			1	1	
LOx/LH2									
H2O2/RP1		3	1				1		
Hybrid	3	1			1				
LOx/Paraffin			1					1	
LOx/Propylene	1								
H2O2/Butane	1								
LOx/Propane			1						
Not identified	4	6	5	1	2	1		1	

Table 22: All launchers by payload and propellant, 0-1500 kg.

All launchers	1.801-1.850	2 000	2.151-2.200	2.251-2.300	2.351-2.400	2.650-2.700	2.851-2.900	3 200	3 450
Solid	1				1	1			
LOx/RP1			1	1					1
LOx/Methane	1								
Hydrazine/N2O4			1		1		1		
LOx/LH2									
H2O2/RP1									
Hybrid								1	
LOx/Paraffin		1							
LOx/Propylene									
H2O2/Butane									
LOx/Propane									
Not identified									

Table 23: All launchers by payload and propellant, >1500 kg.

451-500	501-550	551-600	601-650	701-750	751-800	851-900	951-1.000	1.051-1.100	1.201-1.250	1.301-1.350	1.400-1.450	1.500
1		1		1				2			1	1
1			1		1	1			2			
1						1		1				
									1	1		
									1			
4	1	1					1	1				

3 600	4 400	5.000-5.500	6 450	7 300	8 750	10 500	13 150	13 930	14 900	15 420	15 700	22 850
1	1	1	2		1		1	1				
									1			
				1								
			1			1			1	1	1	1
		2										

Operational	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450
Solid	2		1	3	2	4		1	1
LOx/RP1			1	1					
Hydrazine/N2O4	1			1			1		
LOx/LH2									
LOx/Propylene	1								
Not identified									

Table 24: Operational launchers by payload and propellant, 0-1500 kg.

Operational	1.801-1.850	2 000	2.151-2.200	2.251-2.300	2.351-2.400	2.650-2.700	2.851-2.900	3 200	3 450
Solid	1								
LOx/RP1			1						1
Hydrazine/N2O4			1		1		1		
LOx/LH2									
LOx/Propylene									
Not identified									

Table 25: Operational launchers by payload and propellant, >1500 kg.

451-500	501-550	551-600	601-650	701-750	751-800	851-900	951-1.000	1.051-1.100	1.201-1.250	1.301-1.350	1.400-1.450	1.500
								1			1	
									1			
									1	1		

3 600	4 400	5.000-5.500	6 450	7 300	8 750	10 500	13 150	13 930	14 900	15 420	15 700	22 850
1	1	1			1		1	1				
				1								
						1				1	1	1



Development	0-50	51-100	101-150	151-200	201-250	251-300	301-350	351-400	401-450
Solid	2	1	2	4	1	2			1
LOx/RP1		2	1	3		2	1	1	1
LOx/Methane	1	2		1		1			
Hydrazine/N2O4								1	
LOx/LH2									
H2O2/RP1		3	1				1		
Hybrid	3	1			1				
LOx/Paraffin			1					1	
LOx/Propylene									
H2O2/Butane	1								
LOx/Propane			1						
Not identified	4	6	5	1	2	1		1	

Table 26: Launchers in development by payload and propellant, 0-1500 kg.

Development	1.801-1.850	2 000	2.151-2.200	2.251-2.300	2.351-2.400	2.650-2.700	2.851-2.900	3 200	3 450
Solid					1	1			
LOx/RP1				1					
LOx/Methane	1								
Hydrazine/N2O4									
LOx/LH2									
H2O2/RP1									
Hybrid								1	
LOx/Paraffin		1							
LOx/Propylene									
H2O2/Butane									
LOx/Propane									
Not identified									

Table 27: Launchers in development by payload and propellant, >1500 kg.

451-500	501-550	551-600	601-650	701-750	751-800	851-900	951-1.000	1.051-1.100	1.201-1.250	1.301-1.350	1.400-1.450	1.500
1		1		1				1				1
1			1		1	1			1			
1						1		1				
									1			
4	1	1					1	1				

3 600	4 400	5.000-5.500	6 450	7 300	8 750	10 500	13 150	13 930	14 900	15 420	15 700	22 850
			2						1			
									1			
			1						1			
		2										



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