Introducing a Technical Feasibility Framework for a Commercialized, Low-Latitude SpacePort

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Abstract

Space flight operations have surged in recent years due to an increase in launch services from rising actors in the private sector, commonly known as NewSpace companies. As the demand for launch services increases, the expansion for launch facilities and support infrastructure is comparably anticipated. The present study seeks to determine whether the existence of a low-latitude launch point from Costa Rican territory can constitute the basis of a profitable business model, particularly in the domain of insertion into low-inclination orbits. The investigation parts from a value proposition hypothesis in which launch services and final integration of payload is offered from Costa Rica. It is assumed that reduced launch costs due to geospatial location will generate customer preference for such services, with aspects of the commercial and market analysis left outside the scope of the technical feasibility investigation. The study addresses the value proposition by first materializing the mechanics of launch to orbit from Costa Rican territory. The range of reachable orbits is determined; a trajectory modeling tool for conventional rocket systems was developed and used to generate the trajectory profiles, given a launch latitude and orbital inclination

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requirement. With the orbital mechanics parametrizing the remainder of the analysis, human-environment interaction is considered through aspects such as aeronautical navigation and airspace compliance, infrastructural development and environmental compliance, and operational safety. These form a set of criteria used to propose a series of launch sites that are optimally suited for spacecraft launches. With Costa Rica serving as a case-study, this paper establishes a framework that determines a country's geospatial ability of launching to orbit.

Nomenclature

α	Gravity Turn Angle
β	Launch Azimuth
δ	Latitude
ρ	Air Density
A	Rocket Frontal Area
C_D	Rocket Drag Coefficient
D	Aerodynamic Drag Force
g	Gravitational Acceleration
h	Orbital Altitude
i	Orbital Inclination
m	Rocket Mass
T	Propulsive Thrust Force
t	Time

t_G Time to Gravity Turn

t_{MECO} Time to MECO

V Rocket Velocity

V_e Rocket Exhaust Velocity

V_{orbit} Orbital Velocity

V_{Rot} Rotational Velocity of Earth

AIP Aeronautical Information Publication

ATC Air Traffic Control

DGAC *Dirección General de Aviación Civil*

GEO Geostationary Orbit

GPS Global Positioning System

LEO Low Earth Orbit

MECO Main Engine Cutoff

MEO Medium Earth Orbit

1. Background

To determine the launch location of a spacecraft many factors must be considered; factors related to mission requirements that determine spacecraft size and weight, and mission objectives that determine the necessary orbit for successful completion [1]. Currently there are a collection of launch sites around the world that permit insertion into determined orbits, most of them in the United States, territories of the former Soviet Union, and China, among others. Their locations vary as far north as the Kodiak Launch Complex in Alaska, to the Woomera Launch Site in South Australia. However, launch sites tend to be located near the equator as higher latitudes reduce the range of possible orbital inclinations that can be reached. Additionally, equatorial proximity reduces the amount of energy necessary to reach orbit due to the angular momentum produced by earth's rotation. Sites with high latitudes such as Plesetsk (60^{o}N) or Wallops (37.8^{o}N) are limited to orbital inclinations below 80^{o}, while sites close to the equator such as Korou (5.2^{o}N), Kwajalein Atoll (9^{o}N) or even project Sea Launch–intended for 0^{o} launches [2]–have an almost limitless range of reachable inclinations from their facilities, while benefiting from the added impulse of earth's rotation [1]. The Omelek Island launch center in Kwajalein Atoll, part of the Marshall Islands, became widely recognized between 2006 and 2010 during the SpaceX's Falcon 1 test launches [3]. The remote site was chosen when Vandenberg Air Force Base's was queued with priority launches for NASA, ULA, and established operators [3]. The Guiana Space Center site in Korou, French Guiana was selected by the European Space Agency (ESA) for its equatorial proximity, enabling access to a vast array of LEOs essential to commercial satellite operators. The site is bordered by the Caribbean sea to the East, providing increased safety in the event of launch malfunctions or cascading debris [4]. Both cases of Omelek and Korou support the present study hypothesis that in the context of the crescent commercial launch market, an accessible near-equator launch site with coastal proximity, can constitute the basis of a profitable launch service solution. This, provided that bureaucratic legislation is loosened in the interest of expediting launch services, and the geospatial and orbital mechanic analysis thoroughly establishes the technical feasibility of such an endeavor.

2. Motivation & Technical Overview

In the last decade, NewSpace companies have accounted for a large percentage of commercial space launches, with satellite development holding the largest stake [5]. The satellite imaging industry is forecasted to generate $33 billion only from the manufacture of more than 400 satellites [6]; the SmallSat market is expected to generate similar numbers over the same period [7], with the telecommunication satellite industry expected to generate over $60 billion [8]. The corporate launch market is no exception; SpaceX's global market share in the commercial launch business has grown by about 15% in 2015 to more than 60% in 2018 [9]. This unparalleled growth in commercial space activity reasons the consideration for greater availability of launch infrastructure.

The case for Costa Rica emerges as a result of several factors. The country's pursuit of plasma rocket propulsion and satellite development marks two significant space innovation endeavors. Former Costa Rican astronaut Dr. Franklin Chang Díaz, has helped lay groundwork research for plasma propulsion with the development of the VASIMR engine, through Ad Astra Rocket Company since 2006 [10]. The Proyecto Irazú satellite is the most recent Costa Rican grassroots initiative in space exploration [11]. The 1U CubeSat is assessing fluctuations in biomass growth with respect to atmospheric carbon fixation in Costa Rican forests. The project was the culmination of a transnational effort seeking to obtain more robust data in evaluating forestation trends, and marks a huge leap in the country's effort towards environmental protection technology.

Beyond advances in spacecraft development, Costa Rica boasts the socioeconomic resources necessary to sustain the endeavor of a commercial spaceport. The country is home to more than 250 multinational corporations in the technology industry, which is characterized by a highly educated workforce, an attractive business environment, and lax legislation incentivizing foreign investment [12]. The Costa Rican Legislative Assembly is in process of ratifying a bill for the creation of a Space Registry Office [13]. The creation of the Office comes to adhere to Bill 8838, which stipulates the country's responsibility in maintaining an official record for launched spacecraft, as established in the United Nations Convention on Registration of Objects Launched into Outer Space [14]. The existence of legal and political mechanisms that constitute the regulatory framework for space activities in the country can provide an additional incentive for space companies. Such commercial operators can be interested in a vehicle registration scheme similar to those of maritime offshore vessels, which facilitates operation of marine mercantile fleets to operate in international waters [15]. Beyond legislative and economic considerations, Costa Rica is within optimal equatorial proximity to benefit from the delta-v impulse provided by Earth's eastward rotation, and is at a sufficiently low latitude to reach a wide range of orbital inclinations. This technical hypothesis is the focus of the paper, seeking to determine whether insertion to orbit from Costa Rica permits for a sustained commercial launch service. The approach employed in the investigation is comprehensively discussed in the following section, which aims to consider the challenges at hand from a multidisciplinary point of view.

3. Proposed Methodology

The study is governed by a three-part analysis that (1) materializes the mechanics of launch to orbit from Costa Rican territory, (2) establishes aeronautical compliance and territorial parameters for safe operability, and (3) factors human-environment interaction for sustainable development of launch facilities without obstructing human activity. Within these spheres, this paper proposes a deterministic framework for the provision of launch-to-orbit services.

<u>Geospatial Analysis</u> Ranges of orbits within reach of conventional delivery systems are studied, and whether such orbits can be reached from Costa Rican territory. In this analysis, trajectories of these launch systems are modeled, given a determined launchpoint latitude and desired inclination of orbit. Hence, the only legs of the trajectory that are considered and deemed relevant to the study are vertical ascent, pitch to launch azimuth, and MECO.

<u>Aeronautical Compliance</u> A subset of the orbital-mechanic analysis; this aspect poses a legal challenge with respect to infringement of regional and national airspace. A comprehensive inspection to model the airspace ceiling of the region was conducted, such to determine whether launch trajectories could potentially violate airspace boundaries. Aeronautical corridors, navigation waypoints, and aircraft hold routes in Costa Rican airspace were mapped, which facilitated selection of launch locations that were clear of obstructing air traffic.

Human-Geography Interaction The final aspects considered in the investigation were ogistical operability of the launch site, safety of surrounding populated areas, and environmental compliance. A set of criteria based on these points was established, and further derived from the FAA Draft Environmental [16] Impact Statement for the SpaceX Texas launch site, which stipulated the following requirements:

1. Latitude — The launch site must be in a low-latitude for optimal performance and faster Earth rate.
2. Trajectory — The launch site must be able to support LEO and GTO.
3. Safety — The most favorable launch site would be a coastal site, so that the launch vehicle flies over water and not populated land.
4. Accessibility — The launch site must be easily accessible for delivery of hardware.
5. Climate and Winds — The launch site must have an optimal weather conditions that include low winds, low cloud ceiling, and temperatures above 41 degrees Fahrenheit (F).
6. Size — The launch site must be large enough to incorporate all the necessary facilities, structures, and utility connections in order to support the launch of the Falcon 9 and Falcon Heavy launch vehicles.
7. Diversity — The launch site must be in a different location than other ranges that SpaceX utilizes in order to diversify risk and operations.
8. Schedule Flexibility — The launch site must have a high probability of meeting tight launch windows.
9. Airspace — The launch site must be located in an area with limited airspace disturbance.

While specific to SpaceX, these factors are ideal given that they are of practical interest to private spacefaring companies and generally applicable for the selection of all launch sites. These criterion were cross-referenced to Costa Rica's local geography, with the following geographical requirements being stipulated for site selection:

- 3km accessibility to principal terrestrial routes.
- 5km minimum clearance to the nearest habitation.
- 2km minimum clearance to environmental conservation areas and Ramsar wetlands.

A modus operandi for the provision of launch services is thus proposed, governed by the technical findings from the three spheres of the proposed methodology.

4. Geospatial and Aeronautical Study

The laid methodology is a top-down approach for determining launch feasibility. Orbital physics governs the navigational launch parameters; aeronautical compliance is thereafter factored in to preempt obstructions with air traffic.

4.1. Orbital Mechanics of Low-Inclination Orbital Launches

There are two principal launch-to-orbit decisions that simplify the orbital mechanic challenge. Firstly, given Costa Rica's equatorial proximity at 9.75°N latitude, it is of interest to capitalize on Earth's rotational velocity for lessened fuel expenditure. This phenomenon is more commonly referred to as the delta-V saving, and can be quantified to determine the economics of launching to orbit. Launch windows are thus strictly constrained eastward to benefit from the delta-v impulse. The launch azimuth (β), or navigational vector measured with respect to the North (Figure A.1), specifies the trajectory direction following vertical ascent, and is more rigorously determined by velocity, altitude, and inclination of the desired orbit. Low-inclination orbits are of primary interest, as these directly take advantage of Earth's eastward rotation and are of closest proximity to low-latitude launches. This is vital in reducing fuel consumption and hence, drives down the operational cost per launch. Hence, the corresponding orbits that are within range of optimal insertion are those chosen to be at inclinations of approximately $-35^{o} \leq i \leq 35^{o}$. Furthermore, these consist of GEOs [17], with an altitude of 36,000km, inclination of 0° and velocity of 3km/s; MEOs, featuring an altitude of 20,200km, near-equatorial inclination, and frequented by GPS satellites; select LEOs, located at 100km altitude; and escape trajectories.

Once orbital boundary conditions were established, trajectory modeling tools were developed that (1) would calculate the delta-v saving and launch azimuth, given a determined launch latitude, orbital inclination, altitude, and inclination; (2) would generate trajectory profiles from launch to MECO, given a rocket's fuel burn specifications and pre-determined azimuth. The former is determined by orbital mechanic calculations, while the latter is a derivation of the rocket equation with applied penalties of gravity, drag, and earth's rotational velocity.

4.1.1. Azimuth & Delta-V Analysis

Launch azimuth is calculated based off of spherical trigonometry.

$$\cos(i) = \cos(\delta)\sin(\beta) \Rightarrow = \arcsin(\frac{\cos(i)}{cos(\delta)}) \tag{1}$$

This azimuth assumes an inertial frame of reference, however. We will denote this β_{inert}. The true, rotating frame of launch azimuth is a difference between the inertial vector and the earth's rotation vector. The delta-v relation can be subsequently determined based on splitting the rotational velocity into its vector components. The rotational velocity of Earth at the equator is 465.1m/s and is denoted by V_{eqrot}.

$$v_{inertial} = v_{earthrot} + v_{Rot} \Rightarrow v_{Rot} = v_{inert} - v_{earthrot} \tag{2}$$

$$v_{inertial} = v_{orbit}\langle\sin(\beta_{inert}), \cos(\beta_{inert})\rangle + v_{Rot} \tag{3}$$

$$v_{earthrot} = v_{orbit}\langle\cos(\delta), 0\rangle v_{eqrot} \tag{4}$$

Plugging (3),(4), into (2) yields the rotational velocity.

$$v_{rot} = \langle v_{orbit}\sin(\beta_{inert}), v_{orbit}\cos(\beta_{inert})0\rangle - \langle v_{eqrot}cos(\delta), 0\rangle \tag{5}$$

$$= \langle v_{orbit}\sin(\beta_{inert}) - v_{eqrot}\cos\delta, v_{orbit}\cos(\beta_{inert})\rangle - \langle v_{eqrot}cos(\delta), 0\rangle \tag{6}$$

From this, the rotational velocity can be split into its vector components.

$$v_{rotx} = v_{orbit}\sin(\beta_{inert}) - v_{eqrot}\cos(\delta) \tag{7}$$

$$v_{roty} = v_{orbit}\cos(\beta_{inert}) \tag{8}$$

$$\beta_{inert} = \arctan\frac{v_{rotx}}{v_{roty}} \tag{9}$$

The rotating frame launch azimuth is given by (9), while the delta-v relation can be further derived from (7) and (8).

$$v_{rot} = \sqrt{v_{rotx}^2 + v_{roty}^2} \tag{10}$$

$$\Delta V = v_{inert} - v_{rot} \tag{11}$$

4.1.2. Trajectory Profile Modeling

Once launch to orbital parameters were established, calculating the trajectory profile of rocket systems became of interest primarily to determine potential interference with aeronautical boundaries. The vertical trajectory of the rocket is determined as a function of time, from $t = 0$ to $t = t_{MECO}$, which is when the second-stage rocket ignites and insertion into orbit commences. The vertical trajectory of the rocket is determined by state variables of altitude, velocity, and total mass, which all vary as functions of time as well. These are governed by the following ordinary differential equations (ODEs), which give the time rate of change of each state variable.

$$\dot{h} = V \tag{12}$$

$$\dot{V} = F/m \tag{13}$$

$$\dot{m} = -m_{\dot{f}uel} \tag{14}$$

The forces acting on a rocket are thrust, aerodynamic drag, and gravity. Thus, (13) can be more comprehensively written as

$$\dot{V} = \frac{-mg - D + T}{m} \tag{15}$$

Furthermore, drag and thrust can be expressed by the following equations

$$D = \frac{1}{2}\rho V^2 C_D A \tag{16}$$

$$T = \dot{m}_{fuel} v_e \tag{17}$$

The state variables can then be rewritten as

$$\dot{h} = V \tag{18}$$

$$\dot{V} = -g - \frac{1}{m}\frac{1}{2}\rho V^2 C_D A + \frac{\dot{m}_{fuel} v_e}{m} \tag{19}$$

$$\dot{m} = -\dot{m}_{fuel} \tag{20}$$

Here, $\dot{m}_{fuel}$ and v_e are based on the engine specifications of the rocket. Using Forward Euler Integration, we can time step from $t = 0$ to $t = t_{MECO}$ and discretize the trajectory profile. Following the general form

$$y_{i+1} = y_i + (y_{rate,i})(t_{i+1} - t_i) \tag{21}$$

The ODEs governing the rocket trajectory now become

$$h_{i+1} = h_i + (v_i)(t_{i+1} - t_i) \tag{22}$$

$$v_{i+1} = v_i + (-g - \frac{1}{m}\frac{1}{2}\rho V^2 C_D A + \frac{\dot{m}_{fuel} v_e}{m})(t_{i+1} - t_i) \tag{23}$$

$$m_{i+1} = m_i - \dot{m}_{fuel}(t_{i+1} - t_i) \tag{24}$$

$$\tag{25}$$

(22), (23), (24) are effectively used to govern the trajectory of the rocket during vertical ascent. These equations, however, are slightly manipulated at $t \geqslant t_g$, the time at which the rocket maneuvers to pitch towards its launch azimuth. Here, the trajectory begins to adopt a parabolic profile, where position and velocity can be split into vertical and horizontal components. The position and velocity vectors become, respectively

$$h_{i+1} = h_i + (v_{zi})(t_{i+1} - t_i) \tag{26}$$

$$x_{i+1} = x_i + (v_{xi})(t_{i+1} - t_i) \tag{27}$$

$$v_{z,i+1} = v_{zi} + (\cos\alpha_i)(-g - \frac{1}{m}\frac{1}{2}\rho V^2 C_D A + \frac{\dot{m}_{fuel} v_e}{m})(t_{i+1} - t_i) \tag{28}$$

$$v_{x,i+1} = v_{xi} + (\sin\alpha_i)(-g - \frac{1}{m}\frac{1}{2}\rho V^2 C_D A + \frac{\dot{m}_{fuel} v_e}{m})(t_{i+1} - t_i) \tag{29}$$

$$\tag{30}$$

where α is the vehicle's turning angle measured with respect to its vertical launch vector, and is determined by the rocket's gravity turn settings. Evaluating the state variable equations from launch to the time of MECO results in a parabolic rocket flight path. Strictly determining altitude the rocket's altitude per unit of ground distance covered is crucial for the airspace compliance analysis.

Figure A.2 illustrates a launch-to-MECO profile of a SpaceX Falcon 9 FT along with the vehicle's technical specifications, from the derived relations above. The specified latitude, azimuth, and atmospheric conditions are sampled to simulate a launch from Costa Rica's Atlantic coast.

4.2. Regional Airspace Compliance

Air traffic compliance, while seemingly a navigational concern, is a factor that must be considered in parallel along with the other focuses of the study. From an orbital mechanics perspective, beyond merely being within range of orbital insertion, the horizontal distance covered in the Δt of a rocket's ascent to gravity turn is imperative in determining (1) whether the threshold altitude of air traffic coverage is being exceeded, and (2) whether certain legs of a rocket's trajectory interfere with foreign airspace. In the Costa Rican case, aeronautical navigation charts from the DGAC AIP [18] were consulted to determine the national airspace ceiling, aerial corridors, and aircraft navigational hold routes. Additionally, the airspace of Panama was considered, concerning the potential case where trajectories could crossover neighboring countries.

Costa Rica's airspace is homogeneously Class C, with a service ceiling of 5791.2m (19,000ft) (Figure A.3) [18]. Given the intention of launching eastward, areas along the Caribbean coast are favored to avoid the safety risks associated with flying over land. Hence, the airspace directly above the Atlantic coastline and in the peripherals is examined. Towards the East lies the shared Panama-Centroamérica FIR airspace border, which is Class F and ascends to 5943.6m (19,500ft). Both of these national and foreign airspace ceiling thresholds would need to be surmounted during the leg of vertical ascent for safe operation. Furthermore, eastward launches would facilitate obtaining flight permits for spacecraft, by reducing legislative measures generally required when interfering with foreign airspace.

Once examining general bounds of air traffic coverage, aeronautical corridors and en-route hold routes were identified and designated as criterion for a launch site. Territory adjacent to the Caribbean coastline containing the lowest density of aeronautical corridors, yet in proximity of hold routes, was considered. The latter is necessary for diverting air traffic approaching the launch site to the designated hold routes during launch windows. From Figure A.3 it is immediately observable that hold routes "COLOR" and "LIMON" are favorable to redirect incoming air traffic. The area bounded by corridors A317, A322, B690, and the coast most closely meets the afore listed requirements.

Relevant data from the aeronautical navigation charts (Figure A.4) was mapped alongside rocket trajectories to resolve the airspace compliance concern. The generated launch profile of the SpaceX Falcon 9 from launch to MECO (Figure A.2) is applicable in this example, given a similar launch latitude at 10°. By consulting the trajectory profile plot illustrated in Figure A.2, it is observable that at 5943m (19,500ft), the rocket has surpassed the airspace ceiling while remaining within Costa Rica's territorial and aeronautical boundaries. Modeling the previous relevant data enabled inspection for candidate launch sites, as pinned in Figure A.6.

The proposed locations were ranked in order of geographical importance, with these details being further elaborated upon in the upcoming sections.

5. Human-Geography Interaction

Among the inherent considerations for site selection are factors surrounding human-environment interaction [14]. Once potential launch sites were determined, required spaceport facilities and sustainable integration into the surrounding environment was considered. The selection of the proposed site must pretend to minimize a potential impact on endemic biodiversity and human settlements. Coastal sites were favored with regards to this key factor, as paralleled by the SpaceX EIS [16]. Using QGis v3.0, a distance estimation from each launch site to surrounding points of interest was made. The measurements were made using the WGS 84 ellipse reference projection, issued by the Costa Rica National Geographic Institute.

Aside from coastal proximity, all sites were selected in the Caribbean region due to the need of launching eastward as explained in the aforementioned sections. Precipitation in the Caribbean region approaches 3300mm annually, with a maximum of 4500mm in the northeast region and a minimum of 2700mm to the south of the Turrialba depression. The average year-round temperature approximates 27°C [19]. According to the FAA [20], a year-round temperature above 5°C is recommended for launch, with low wind profiles and clear visibility. The possibility of establishing seasonal launches should be considered, due to weather variability in the Caribbean region.

Four potential sites were proposed for analysis and categorized according to average viability among all variables.

1. Sara, Batan, Limon: located at coordinates, 10 7'5.53"N, 8321'24.60"W, it

has a minimal distance to the coast and to the maritime port terminals of Moin and APM. The nearest aerial route lies 3.08 km away; the airspace boundary for the Limón Airport lies 20.70 km away while the airspace limit for the Juan Santamaría International Airport lies at 35 km. This site is located at 7.5 km from La Amistad conservation area (ACLAC) in the Pacuare river sector. The nearest protected wetlands are 3.4 km away and the coastline lies 14.07 km to the east near the Pacuare river mouth. The nearest populated center is a town named Sara located 1.9 km away. The access to the first order national road 32 is 5.15 km, and access to second order regional route 805 is 4.55 km away. The maritime ports mentioned are located at around 30 km from this site.

2. Trinidad, Pocora, Limon: located at coordinates, 109’19.08”N, 8332’35.58”W. This site is located 3.08 km away from the Limón airport airspace limit, and 21.70 km from the Juan Santamaría International airport. It is located 7.5 km from Reventazón river basin and 3.4 km from central Caribbean Wetlands. Trinidad is 27.20 km away from the shore near the Parismina river. The nearest populated area is a town named Herediana located 2.6 km away. The nearest first order national route 32 is just 4.52 km away while the second order regional route 805 is at 1.38 km. The site is 50.75 km from APM terminals and 53.95 km from the Moín port.
3. Guácimo, Limón: located at coordinates 1012’57.40”N, 8338’40.82”W, this site is located 11.13 km from the nearest aerial route and 6.14km from Juan Santamaría airspace limit. The site is also 14.4km north of the Turrialba Volcano, which is part of the Central Volcanic Mountain Range Forest Reserve, and is 8km away from the central Caribbean Wetlands. The coastline lies 33km east in what is part of the Tortuguero National Park. This site is located 5.36 km from EARTH University’s main campus and 2.64 km from the Guácimo town. This site is only 2.27km away from first order national route 32 and 63.58 km away from APT maritime port.
4. Saino, Pital, San Carlos: is the farthest of the studied sites. Its analysis, however, could provide a valuable data point for comparison. Its coordi-

nates are 1033'58.10"N, 8418'12.50"W. It is located 17.35 km away form the nearest air route and 4.15 km away from the Juan Santamaría International airspace limit. It is located 20.45km away from La Curena forest reserve, that is part of the Atlantic-North Huetar Conservation Area and is 3.90km away from protected wetlands. This site is approximately 80km west of the Caribbean coastline. The nearest populated area is Saino at 2.4 km. Second order regional route 250 is at 2.4 km, while access to third order rural route is at 0.4 km. This site does not have access to first order national routes, with the main maritime ports lying 145 km away.

The data from the previous analysis is summarized in Table B.1. Sites 1 and 2 share sufficient proximity with the shoreline, as well as main route 32 and the maritime ports. Regarding distance between airways, restricted airspace, and protected areas, sites 3 and 4 likewise satisfy these requirements. However, the distance of sites 1 and 2 to this space is sufficient to prevent obstruction with air traffic and protected land. The last point left to be evaluated is the distance to populated centers; in this criterion all four sites are situated in a radius between 1.9km to 2.6 km to inhabited areas–thus, population is not a decisive criterion. In conclusion sites 1 and 2 denominated Sara and Trinidad, both in the Limon province, are the best choices from the given set of geo-analytical criterion.

6. Operations and Infrastructure Considerations

Alexander Ostewalder defines a methodology to propose a strategy roadmap for delivering or capturing value [21], with this model serving as a baseline for operational considerations. The present study proposes a hypothesis based on offering launch services and final payload and spacecraft integration from Costa Rica. Ostewalder's framework is employed to deliver and capture value in the country's economy with the use of space technology. According to Eric Ries, the process of value creation involves extreme uncertainty, therefore implementation of effective ways for measuring empirically acquired learning is necessary [22]. This validated learning will come from experimentation aimed to prove the proposed launch services hypothesis. From this study, perspective generation of this empirical learning process seeks to outline and evaluate whether the existence of key resources such as geographic location, facilities and infrastructure in a low-latitude country such as Costa Rica, can generate a feasible project with positive impact for the country's economy.

The importance of multinational access to space science technology is of great importance to developing countries as emphasized by the United Nations General Assembly in 2016. Among the goals endorsed in 2018 by the United Nations Committee on the Peaceful Uses of Outer Space, global partnership in space exploration and innovation was given high priority due to the great prospect of multilateral collaboration in promoting space accessibility. Indigenously paving a country's access to space is a multifaceted endeavor that firstly requires fostering an educational bedrock of technical know-how. This in turn will determine the domestic capability of developing required facilities and more importantly spacecraft, thus ultimately leading to launch self-sufficiency. New initiatives to complement current efforts should go beyond educational outreach and data provision; international collaboration for space exploration should address the technical limitations of developing countries that has hindered such in obtaining equal access to space [23].

An effort spearheaded by Argentina and seconded by Brazil to establish a South American Space Agency has taken place over the past ten years; however, implementation of the entity has been sluggish. It is important to note that even developing countries pursuing satellite programs, such as Venezuela, Bolivia, Chile, and Peru, whereas nations such as Argentina and Brazil developing launch infrastructure, mutually require of a platform providing access to space services. Furthermore, the proposal of the agency has sought to grant political independence in the interest of pursuing space agenda, while giving signatories greater, unified leverage during international negotiation. A study performed by a group during the 2015 South American Space Generation Workshop in Argentina determined an increase in regional demand for launch services, particularly from China and ESA (Korou). The trend appears to continue as private entities, governments, and organizations within the region seek to integrate efforts to promote access to space [24]. In this scenario, the demand for regional launch capabilities independent from Europe, USA, China and Russia could represent an interesting market [24].

The economic implications of a spaceport presence holds promise for regional investment and employment incentives. In drawing space enterprises to Costa Rican soil, private and public organizations would enable the creation of bi-directional pipelines of scientific knowhow, particularly for spacecraft research and development. The Guiana Space Center is most similar in this regard, bringing together Roscosmos, Italy's ELV, and ArianeGroup. Similarly, a Costa Rican spaceport would aim to foster partnerships transcending borders and corporations. Furthermore, the ELA Korou launch site was closely modeled after for required launch facilities [4].

Of the discussed Costa Rican candidate sites, Trinidad was favored based on proximity to the coast, main roads, and ports, while being sufficiently clear of controlled airspace. Based on the Korou specifications, the selected location would adequately house facilities such as control centers, satellite preparation facilities, propellant plants, launcher integration facilities, final assembly building, and a launch pad. These have been modeled in Figure A.6, as developed from satellite renders of the Trinidad launch site.

7. Foreseen Challenges

7.1. Legal Barriers

The prime challenge surrounding the provision of launch services from Costa Rica, is challenging ITAR constraints that currently limit NewSpace companies to launch from U.S. soil. Such legislation pose a significant barrier in pivoting from government to industry-regulated space exploration, particularly as the demand for launches increases annually. In spite of this, the prospect for legal overhaul is promising. NASA has had a small, though prolonged presence in Costa Rica. Most prominently was the presence of NASA's Tropical Cloud

Systems and Processes Mission, carried out between 2000-2010 [25, 26], where gas fixation in the tropopause was studied, along with meteorological conditions in the troposphere and stratosphere. The experimental WB-57 aircraft was stationed in San José during missions that studied tropical cyclone formations. The aircraft and supporting laboratories significantly contributed to the study of hurricane genesis in the eastern Pacific, with the center of the investigation occurring out of Costa Rica.

NASA has collaborated extensively with Ad Astra and the VASIMR rocket engine, notably through awarding research grants and tests aboard the KC-135A aircraft [27]. The VF-200 VASIMR Engine includes High Temperature Superconducting (HTS) magnet assemblies that are conduction-cooled by cryocoolers. Flights aboard the aircraft allowed for characterization of the cryocoolers' natural vibrational modes at varying gravity levels, enabling Ad Astra to down-select the use of its particular cryocooler and properly design vibration mitigation mechanisms for proper function of the VASIMR engine. While these are unique examples, the groundwork for legislative collaboration is certainly present, serving opportune for exploring bilateral partnership in the provision of launch services.

7.2. Environmental Protection

Costa Rica is known for having adopted one of the world's most rigorous environmental protection policies. This presents the next concern in drafting legislation for launch operations. Ramsar protected wetlands constitute a large percentage of the landscape of the Caribbean, and were thus factored in the criteria for site selection. Protection of these locations, among others such as, biological reservations, national parks, and wildlife reserves, among others, must be addressed when considering the perturbation of land mandated by the state to be under environmental protection.

As stipulated by Bill No. 7554 [28], which details the necessary mechanisms adopted by the state to maintain Costa Rica's environmental integrity, Articles 17 and 37 are of main importance. These stipulate that all protected land considered for socio-economic development shall be subjected to due investigation to ensure environmental quotas are being met. The processes involved with obtaining due environmental clearances are beyond the scope of this paper, and are merely being highlighted as factors in case development of a launch center is to be indeed carried out.

8. Conclusion

It is important to stress from the findings of this investigation that while Costa Rica is the basis for the present case-study, the framework introduced in this paper for assessing the feasibility of launch services is not exclusive to a single nation. The three-pronged analysis of orbital mechanics, aeronautical compliance, and human-geography interaction can effectively be adopted in the preliminary steps towards determining a country's ability for launching spacecraft.

Within the sphere of orbital mechanics, it is in the interest of nations to capitalize on their respective latitudes and determine optimal orbits within range of insertion. Similarly, understanding the architecture and system of air traffic management in a nation is imperative for ratifying spacecraft flight legislation, particularly in the absence of a formal governing space body. Geographical criterion for site selection will generally vary between countries, though factors such as coastal proximity, accessibility, and limited airspace disturbance among others, would be most commonly considered.

In spite of the recent strides made in advancing space technology, scientific and production costs continue to hinder the development of aerospace systems, as do bureaucratic and legislative barriers. Creating bidirectional pipelines of aerospace development know-how between universities and developing countries, creating spaces for satellite innovation in technical institutes, and establishing multilateral space alliances, are examples of steps needed to be taken in bolstering programs. As spaceflight continues to proliferate, space exploration inches towards become an ever-global, multifaceted endeavor, in which developing countries must equivalently be stakeholders. Through this paper, we seek to provide a cohesive tool that will enable more spacefaring nation-states to flourish.

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Appendix A. Figures

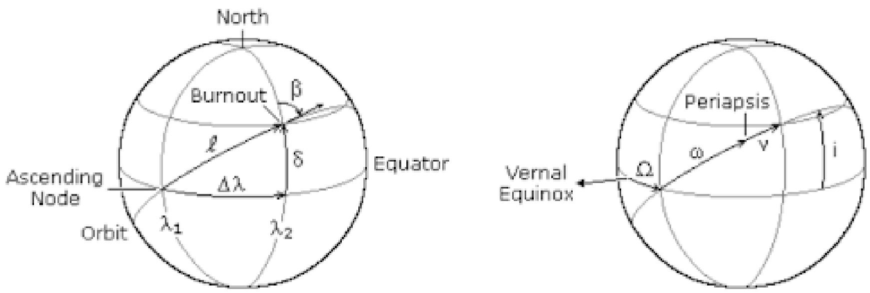
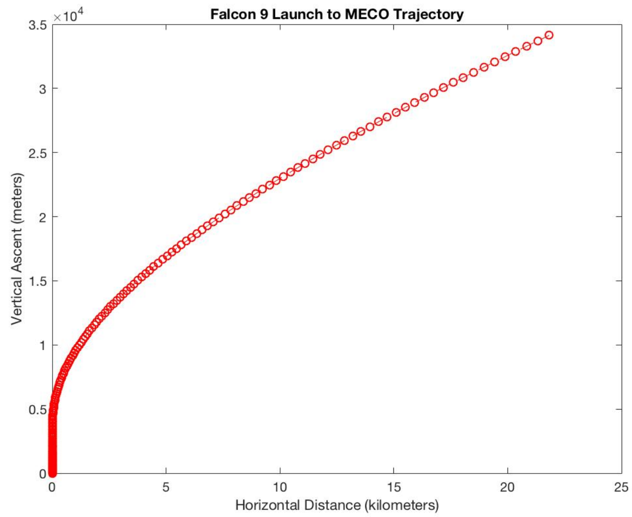
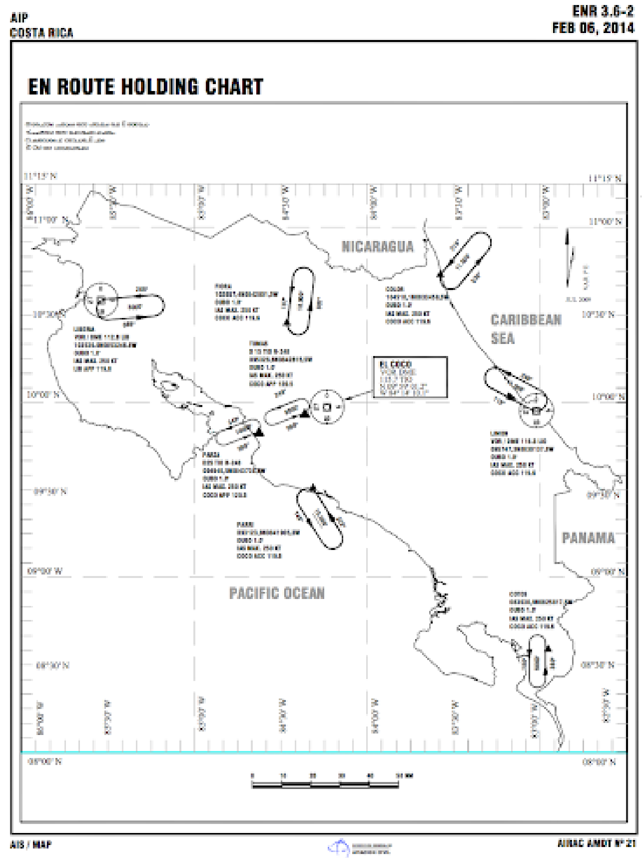


Figure A.1: Visualization of relations between orbital inclination, latitude, and launch azimuth.



β	$80°$
δ	$10°$
i	$0°$
C_D	0.25
A	$22.1m^2$
m	549054kg
v_e	235.4m/s
$\dot{m}$	2764.8m/s
t_G	55s
t_{MECO}	174s

Figure A.2: SpaceX Falcon 9 FT Launch-to-MECO trajectory profile (U) and vehicle specifications (D). 10°sample launch latitude, 0°orbital inclination corresponding to an 80°launch azimuth.



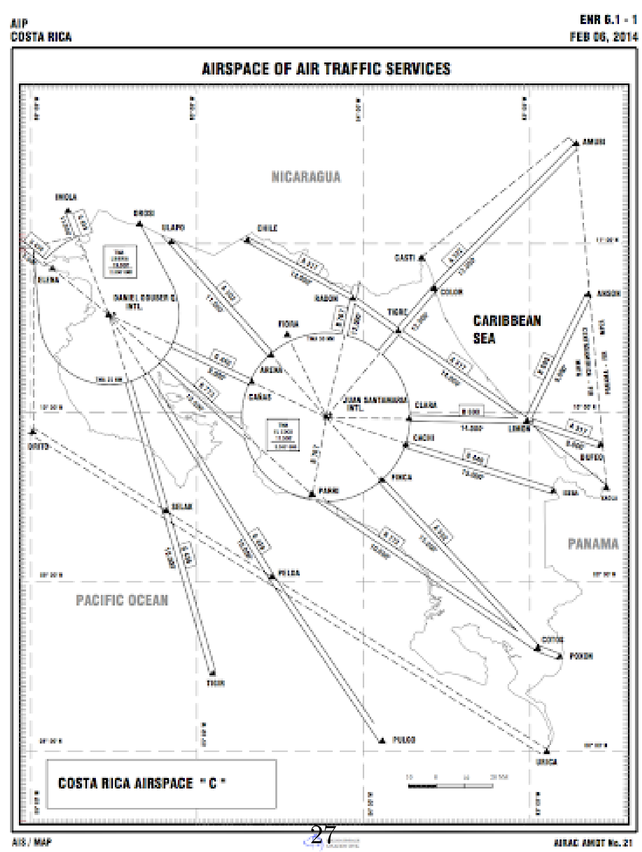


Figure A.3: Aeronautical hold routes in Costa Rican airspace (U), aerial routes and ATC coverage (D).

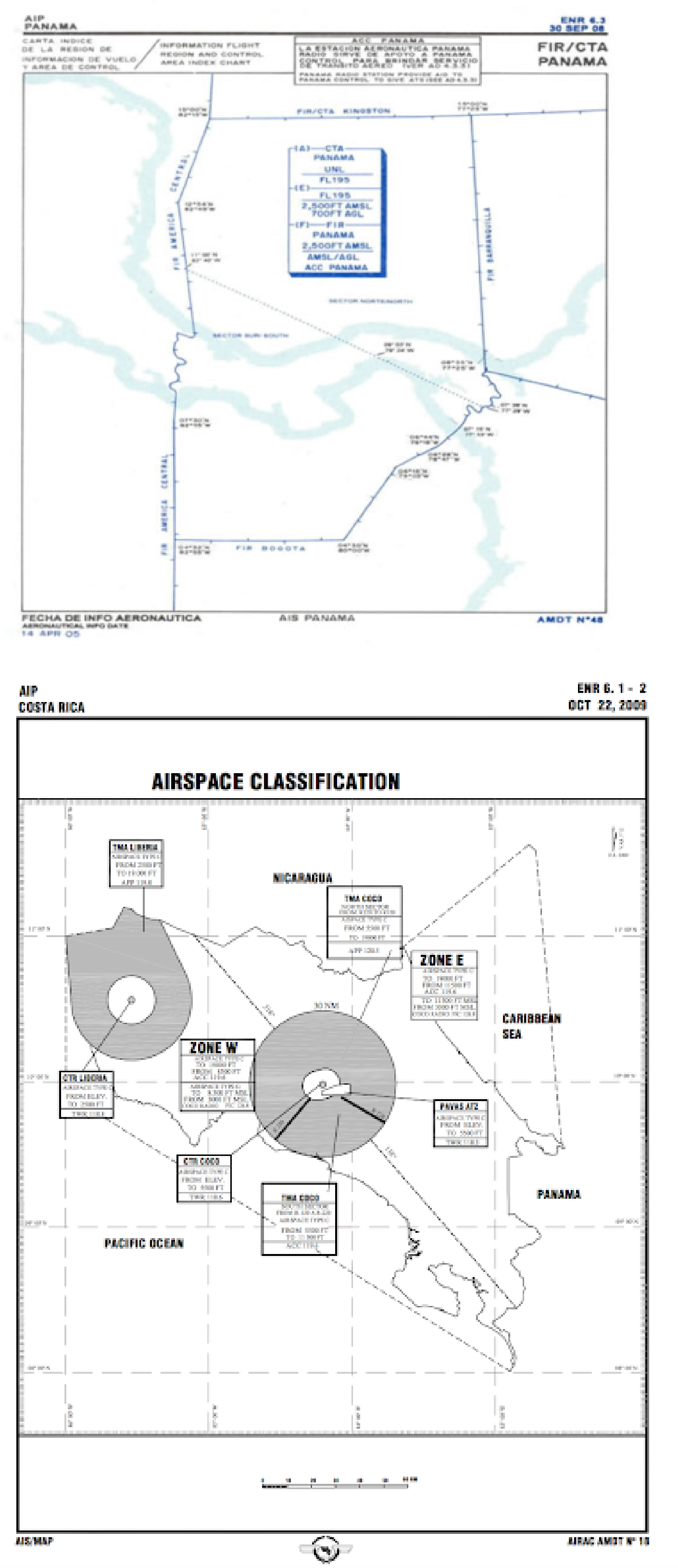


Figure A.4: Panama-Central America FIR border (U), Costa Rica airspace categorization (D).

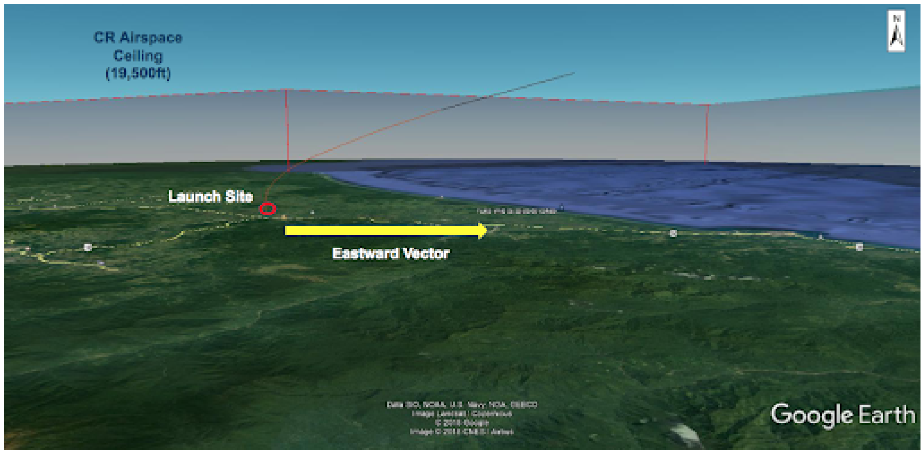


Figure A.5: Costa Rica airspace ceiling, launch point and trajectory visualization.

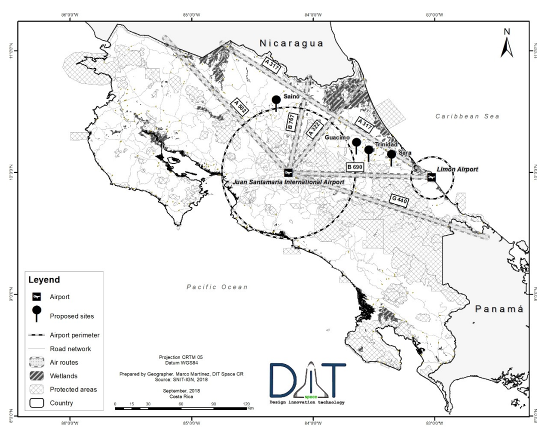


Figure A.6: Proposed candidate sites, from North-west to South-east; Saino, Guacimo, Trinidad, and Sara.

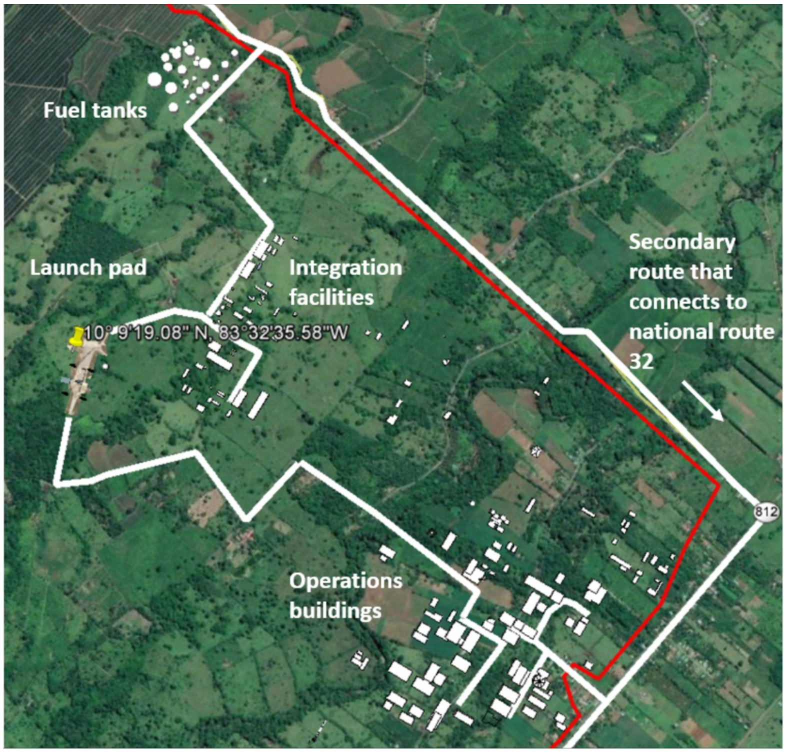


Figure A.7: Spaceport facilities layout, Trinidad site.

Appendix B. Tables

Site	Distance from Airways/Airport Perimeters (km)	Distance from Conservation Areas/Wetlands (km)	Distance to Coast (km)	Distance to Populated Areas (50+) (km)	Distance to Roads: 1st Order National Routes/2nd Order Regional Routes (km)	Distance to Main Maritime Ports: APM Terminals/Moin (km)
1. Sara	3.08 / 21.70	7.50 / 3.40	14.07	1.90 (North)	5.15 (R.32) / 4.55 (r.805)	30.30 / 33.45
2.Trinidad	10.94 / 14.75	7.64 / 4.40	27.20	2.60	4.52 (R.32) / 1.58 (r.812)	50.75 / 53.95
3. Guacimo	11.13 / 6.14	20.8 / 8	33.3	5.36 (EARTH Uni) / 2.64 (Guacimo)	2.27 (r.32)	63.58
4 Saino, Pital	17.352 /4.15	20.45 / 3.90	80.5	2.40 (Saino)	3.90 (2do orden) / 0.4 (r. muni)	N/A

Table B.1: Ranking of potential launch sites by preferred distance criterion.