International Telecommunication Union

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(09/2019)

Radiocommunications for suborbital vehicles

M Series

Mobile, radiodetermination, amateur and related satellite services

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S	Fixed-satellite service
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SM	Spectrum management

***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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Radiocommunications for suborbital vehicles

(2019)

Keywords

Suborbital vehicle; Spectrum; Radiocommunications

Glossary/Abbreviations

ACC	Area control centre
ADS-B	Automatic dependent surveillance-broadcast
ADS-C	Automatic dependent surveillance-contract
ANSP	Air navigation service provider
ATC	Air traffic control
DME	Distance measuring equipment
GLONASS	Globalnaya navigatsionnaya sputnikovaya sistema (Global navigation satellite system)
GNSS	Global navigation satellite system
GPS	Global positioning system
GSO	Geostationary-satellite orbit
ICAO	International Civil Aviation Organization
NCO	Numerical controlled oscillator
NM	Nautical mile
RR	Radio Regulations
SFC	Surface
UNL	Unlimited
SoV	Suborbital vehicle
SSR	Secondary surveillance radar
TCAS	Traffic alert and collision avoidance system
TDRS	Tracking and data relay satellites
TFR	Temporary flight restriction
UAT	Universal access transceiver
VHF	Very high frequency

Related ITU-R Recommendations and Reports

Recommendation: ITU-R P.531-13 – Ionospheric propagation data and prediction methods required for the design of satellite services and systems

1 Introduction

This Report, in response to Question ITU-R 259/5, provides information on the current understanding of radiocommunications for suborbital vehicle (SoV) use including a description of the flight trajectory, categories of suborbital vehicles, technical studies related to possible avionics systems used by suborbital vehicles, and service allocations of those systems. Through Question ITU-R 259/5 the Radio Assembly decided that the following three questions should be studied:

1) How will planes be operated including a description of the various phases of flight?

2) During which phases of flight described in *decides* 1, will, if at all, need to be supported by air traffic control (ATC) systems and what sort of systems are expected?

3) What radio links will be required to support planes operations and under what radiocommunication service definition will they fall?

2 Definitions

Various definitions related to SoV and space planes are provided in this section. Where there is not an RR Number stated, these definitions are not established in the RR and are applicable only to this ITU-R Report. It has not been established if components or items of current space satellite launcher systems may be considered suborbital vehicles from a radio communications perspective:

Aeronautical station: A land station in the aeronautical mobile service (see RR No. **1.81**).

Aeronautical mobile service: A mobile service between aeronautical stations and aircraft stations, or between aircraft stations, in which survival craft stations may participate; emergency position-indicating radiobeacon stations may also participate in this service on designated distress and emergency frequencies (see RR No. **1.32**).

Aeronautical mobile-satellite service: A mobile-satellite service in which mobile earth stations are located on board aircraft; survival craft stations and emergency position-indicating radiobeacon stations may also participate in this service (see RR No. **1.35**).

Aeronautical mobile-satellite (R) service: An aeronautical mobile-satellite service reserved for communications relating to safety and regularity of flights, primarily along national or international civil air routes (see RR No. **1.36**).

Aeronautical earth station: An earth station in the fixed-satellite service, or, in some cases, in the aeronautical mobile-satellite service, located at a specified fixed point on land to provide a feeder link for the aeronautical mobile-satellite service (see RR No. **1.82**).

Aircraft: Any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the Earth’s surface (Annex 1 to the Convention on International Civil Aviation).

Aircraft station: A mobile station in the aeronautical mobile service, other than a survival craft station, located on board an aircraft (see RR No. **1.83**).

Aircraft earth station: A mobile earth station in the aeronautical mobile-satellite service located on board an aircraft (see RR No. **1.84**).

Doppler acceleration: The rate of change in frequency or wavelength of a wave in relation to a frame of reference who is accelerating relative to the wave source.

Inter-satellite service: A radiocommunication service providing links between artificial satellites (see RR No. **1.22**).

Orbit: The path, relative to a specified frame of reference, described by the centre of mass of a satellite or other object in space subjected primarily to natural forces, mainly the force of gravity (see RR No. **1.184**).

Satellite: A body which revolves around another body of preponderant mass and which has a motion primarily and permanently determined by the force of attraction of that other body (see RR No. **1.179**).

Spacecraft: A man-made vehicle which is intended to go beyond the major portion of the Earth's atmosphere (See RR No. **1.178**).

Space operation service: A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand (see RR No. **1.23**).

Space research service: A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes (see RR No. **1.55**).

Mobile-satellite service: A radiocommunication service between mobile earth stations and one or more space stations, or between space used by this service; or between mobile earth stations by means of one or more space stations. This service may also include feeder links necessary for its operation (see RR No. **1.25**).

Radio astronomy: Astronomy based on the reception of *radio waves* of cosmic origin (see RR No. **1.3**).

Radiocommunication: Telecommunication by means of radio waves (see RR No. **1.6**).

Radionavigation-satellite service: A radiodetermination-satellite service used for the purpose of radionavigation. This service may also include feeder links necessary for its operation (see RR No. **1.43**).

Radiotelemetry: Telemetry by means of radio waves (see RR No. **1.132**).

Re-entry: Re-entering into the atmosphere to a certain altitude from the highest point of the Earth's atmosphere.

Satellite: A body which revolves around another body of preponderant mass and which has a motion primarily and permanently governed by the force of attraction of that other body (see RR No. **1.179**).

Space plane: A winged vehicle that performs as an aircraft while in the atmosphere and as a spacecraft while in space.

Space station: A station located on an object which is beyond, is intended to go beyond, or has been beyond, the major portion of the Earth's atmosphere (see RR No. **1.64**).

Space telemetry: The use of telemetry for the transmission from a space station of results of measurements made in a spacecraft, including those relating to the functioning of the spacecraft (see RR No. **1.133**).

Space radiocommunication: Any radiocommunication involving the use of one or more space stations or the use of one or more reflecting satellites or other objects in space (see RR No. **1.6**).

Suborbital flight: The intentional flight of a vehicle expected to reach the upper atmosphere with a portion of its flight path that may occur in space without completing a full orbit around the Earth before returning back to the surface of the Earth.

Suborbital vehicle: A vehicle executing suborbital flight.

Telemetry: The use of telecommunication for automatically indicating or recording measurements at a distance from the measuring instrument (see RR No. **1.131**).

Terrestrial radiocommunication: Any radiocommunication other than space radiocommunication or radio astronomy (see RR No. **1.7**).

3 Discussion

This Report provides a description of the flight trajectory, categories of SoV, technical studies related to possible avionics systems used by SoV, and service allocations of those systems. It is noted that:

- some of these frequency ranges include aeronautical allocations used by ATC systems and thus are considered safety-of-life;
- the delimitation between atmosphere and outer space has not been legally defined at an international level by the competent organizations;
- the definitions of status of the stations for suborbital flights for radiocommunication purposed by ITU-R do not prevent the competent international organizations (International Civil Aviation Organization (ICAO), United Nations Office for Outer Space Affairs) to potentially propose in the future, relevant definitions or other orientations concerning the kind of law (air law, space law, sui generis) which could be applicable for the various types of suborbital systems concepts and projects;
- the current satellite/space launch systems including re-usable parts are already operated under the RR;
- ICAO has begun efforts to change aeronautical system standards to support possible use of that equipment by craft flying at altitudes above the commonly used demarcation of the boundary between the Earth's atmosphere and space;
- there is a potential for collisions between SoV and aircraft, which is currently mitigated on a case-by-case basis by airspace authorities and in the future maybe by an integrated ATC and management system that ensures the separation of aircraft and SoV.

4 Description of suborbital flight

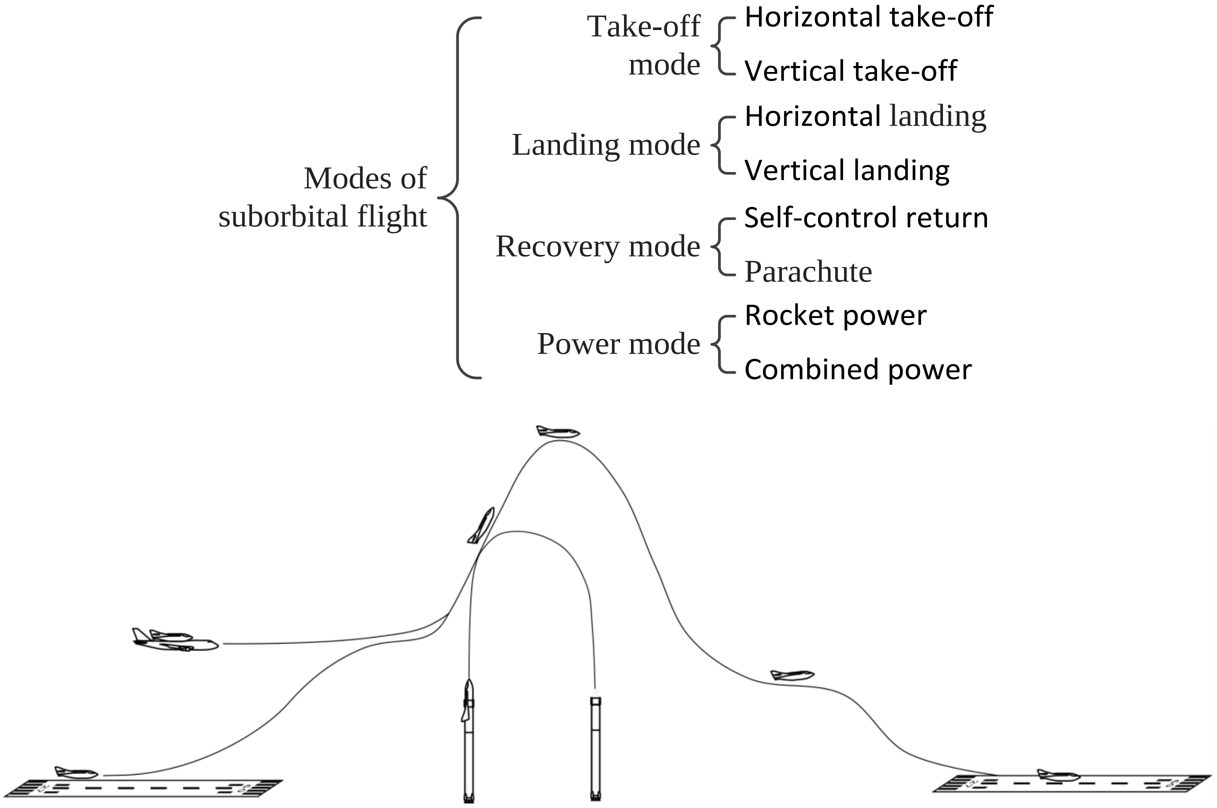
There are plans being developed for suborbital flight based on various types of technologies. The approaches vary between those using a single vehicle and those that use a launch vehicle that carries the SoV up to an intermediate height before releasing the SoV to accelerate into a suborbital flight. The SoV may be inhabited or un-inhabited.

Advances in propulsion technology by both air-breathing power and rocket power has allowed for the design of vehicles which may reach altitudes and velocities not associated with conventional aircraft. These new aerospace systems may use one or multiple forms of new propulsion technologies in several different configurations to achieve suborbital flight. Other types of vehicle designs include stratospheric balloons and part(s) of launch vehicles that don't reach space, so these may fall under the ICAO's definition of an aircraft.

Currently, there are a variety of technical solutions to achieve suborbital flight: take-off modes include horizontal take-off and vertical take-off, landing modes include horizontal landing and vertical landing, recovery modes include self-controlled return and parachute recovery, thrust modes include rocket power and combined power. Suborbital flights can be implemented by different combinations of the above modes. Figure 1 shows different modes of suborbital flight.

FIGURE 1

Different modes of suborbital flight



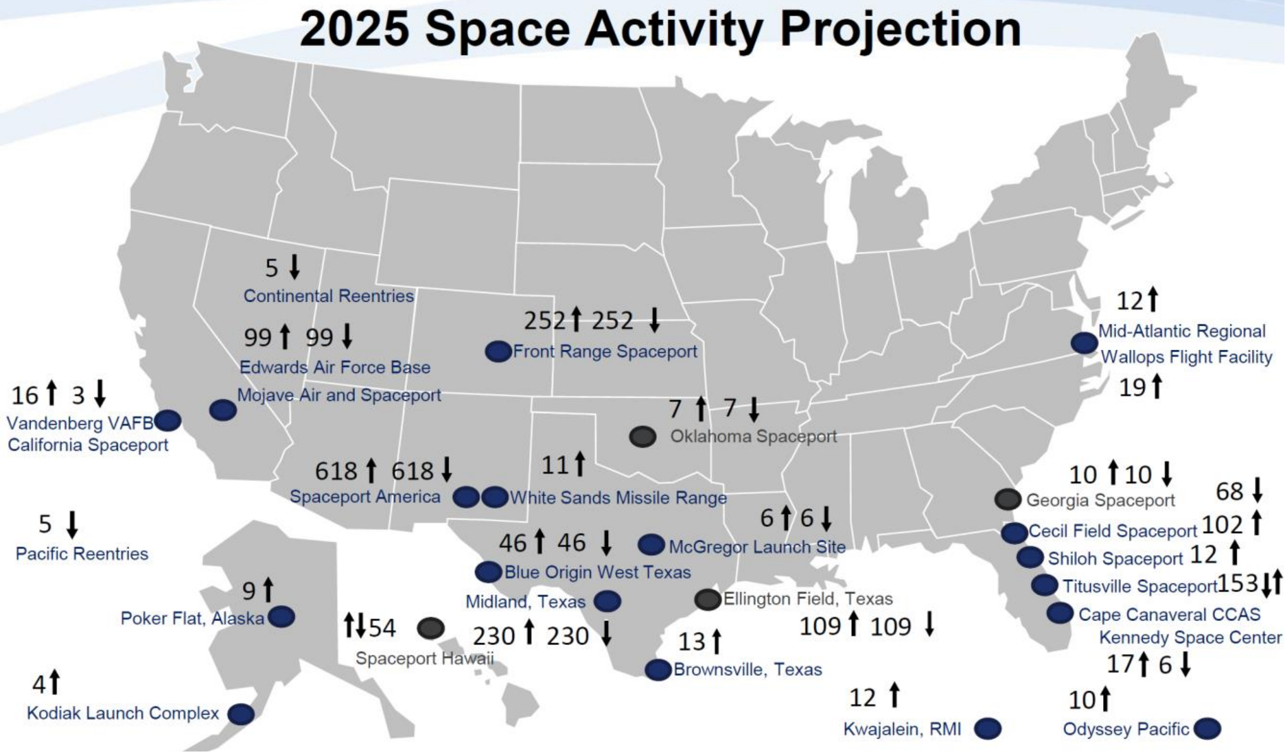
NOTE – The previous Figure does not prejudge the altitude peak of both trajectories.

4.1 Future plans for suborbital vehicles

The global demand for space launches is increasing and new methods of accessing space will help meet that demand. At least, one administration predicts an increase in global commercial launch activity to meet the increasing demand for access to space. Figure 2 shows locations of existing and proposed launch and re-entry locations in one country projected for the year 2025, with the proposed number of launches indicated with an up arrow and re-entries with a down arrow. Not all projections forecasted will be launched, but the trend in the number of launches is increasing and will occur in locations that are not traditional launch ranges. Additional examples of suborbital flight are provided in Annex 6.

FIGURE 2

Projection of 2025 space activity



The launch and re-entry facilities that are relatively new will not have the traditional launch telecommunications infrastructure, such as the facilities co-located at airports. To provide for seamless integration in non-segregated airspace between aircraft and spacecraft, sub-orbital vehicles may need the capability to use equipment that is interoperable with existing air traffic management systems.

When operating in an area controlled by an air navigation service provider, some SoV may be required to be equipped with the same aeronautical systems operating under the same ICAO standards as other aircraft operating in that same airspace and this equipment would therefore fit into the existing aviation radio services. These vehicles would be expected and possibly required to communicate with other aircraft and air traffic controllers in the same spectrum as other aircraft. There is no internationally agreed boundary between the Earth’s atmosphere and the space domain.

An international agreement(s) concerning SoV and flight operations would probably be set forth to deal with issues such as liability, safety, equipment certification and traffic management in line with standards developed by ICAO. The path towards the application of a uniform set of procedures and practices could be performance-based to allow for more flexibility in innovation and stay in full compliance with the current safety, security and environmental requirements.

5 Radio frequency use during suborbital flight

Compared to conventional aircrafts, SoV can travel intercontinentally within a short period for transportation, tourism, etc., at higher altitude and faster speed, which may cause technical and operational issues to current aviation and satellite systems.

With the rapid development of the suborbital technology in recent years, suborbital flight is becoming a reality, which can be applied in a wide range of fields including education, transportation, tourism, scientific research, etc., as shown in Table 1.

TABLE 1

Examples of applications of suborbital flight

No.	Fields	Applications
1.	Space transportation	Provide space transportation of cargo or passengers, including tourism
2.	Scientific research	Provide scientific research for companies and scientific research institutes (space science, biological and physical research, environmental exploration, geoscience, somatic science)
3.	Technology testing and demonstration	Promote the maturity of space industry, test and demonstrate new technologies
4.	Deployment of satellite launcher	Deploy launchers of satellites
5.	Remote sensing	Collection of earth data for commercial or civilian use, such as earthquakes and other natural disasters
6.	Astronauts training	Experience of micro-gravity for astronauts training more representative than under water, longer time than can be achieved by conventional aircraft

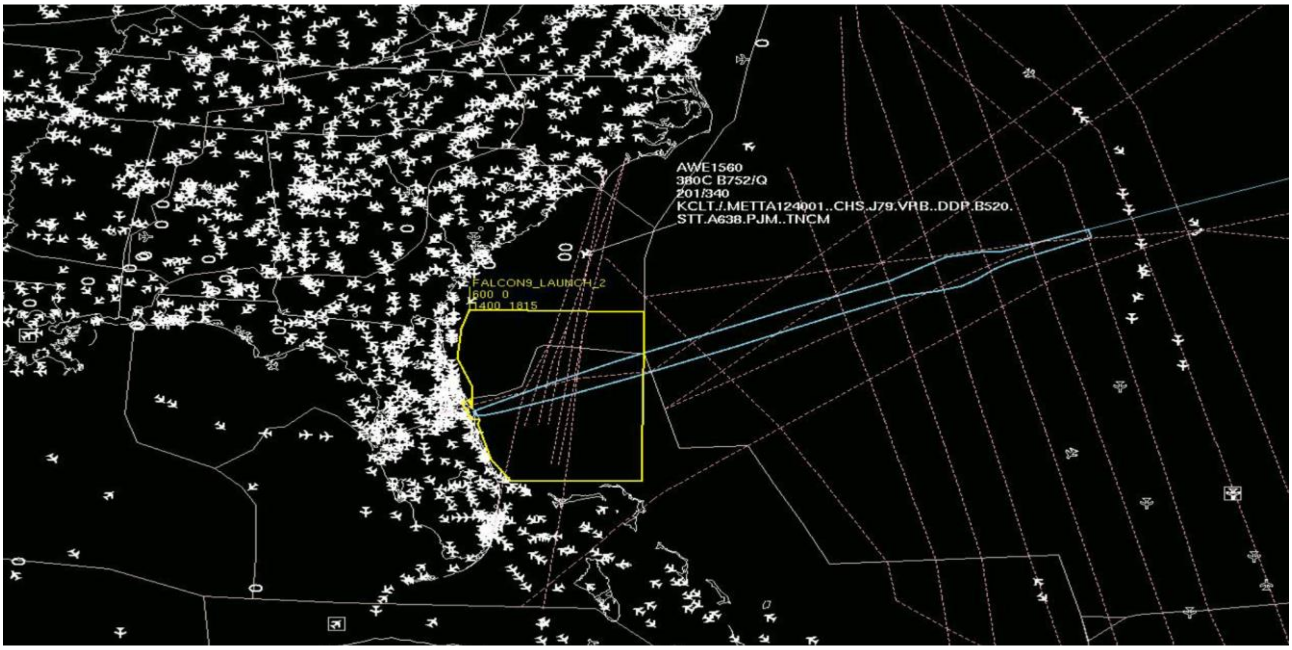
5.1 Operational and technical considerations of suborbital vehicles

SoV must integrate safely into the same airspace as conventional aircraft during their transition to and from space. To maintain airspace at acceptable safety levels, administrations will need to take into account mitigations for international and domestic air cargo and air transportation carriers. Air navigation service providers currently ensure safety by completely segregating SoV from other vehicles during launch and re-entry operations in three spatial dimensions and in time to maintain the required level of safety. This protects the aircraft not only from the launch of the vehicle, but possible debris that could fall on the aircraft during certain periods of the launch. The dimensions of the segregated airspace are driven by existing launch range facility communications capability. The current airspace segregation approach comes at the expense of space launch and re-entry opportunities, air traffic efficiency, and additional fuel and time required for aircraft to avoid hazardous areas. This method of separating space launch and re-entry operations from air traffic will not be sustainable with the increase in demand for space access by additional sub-orbital vehicles operating on and off traditional ranges. Current approaches for airspace efficiency have worked on optimizing the launch trajectory, time of the airspace restriction, and size of the airspace restriction. Some of the current methods used are listed in Annex 1.

Figure 3 shows live air traffic data that was recorded during a SoV launch activity that later included a controlled re-entry back to the surface of Earth. Note the massive amount of international and national airspace that is made unavailable during the launch and re-entry window. The left and right areas around the launch range, show the large exclusion area for international and national flights to safely avoid the launch and re-entry area, which results in additional aircraft fuel consumption, extra travel time, and constrains any launch opportunities because of these airspace disruptions.

FIGURE 3

Live air traffic situational awareness during a launch and re-entry event



Current existing terrestrial civil aeronautical services are primarily designed to support aircraft at altitude up to 21 km. To improve the safety of existing international civil aircraft without extended interruptions to airspace, it may be necessary to equip SoV with internationally standardized aviation systems.

The technical characteristics of suborbital high-altitude flights necessitate the consideration of many factors during all possible phases of suborbital flights including:

– horizontal and vertical flight trajectories which may be significantly expanded;

– maneuverability of SoV;

– predictable density of airspace for each portion of the trajectory.

A proactive approach could be sought for future operations of suborbital flights to avoid or limit the fragmentation of airspace. Some of the important challenges to optimizing a heterogeneous traffic management are:

– positioning, routing and traffic separation;

– collision avoidance for manned and unmanned suborbital traffic;

– optimization of traffic flows under launch uncertainty and imprecise re-entry.

5.1.1 Communications and navigation

Parameter data from a SoV needs to be transmitted to the ground for real-time analysis of suborbital flight. When used for manned space flight, SoV should be equipped with voice communication equipment, which can support voice services between the crew and ground control centre. During some or all phases of flight, depending on the mission, SoV may have to be able to communicate with ATC by internationally standardized systems such as VHF and controller-pilot data link communications for ATC communication.

SoV will also need to be able to navigate their proposed flight path or trajectory.

5.1.2 Surveillance

To improve situational awareness to other international civil aircraft and to aid air navigation service providers (ANSPs) or different operators in separating aircraft from suborbital flight the SoV will use automatic dependent surveillance-broadcast (ADS-B) out on 978 MHz or 1 090 MHz Other internationally standardized terrestrial and space aeronautical systems may also be used for surveillance purposes.

5.1.3 Telemetry, tracking, and command

Telemetry, radio telemetry and space telemetry are defined in RR Nos. **1.131**, **1.132** and **1.134** respectively. They provide vehicle status and other information. A payload could have its own dedicated spectrum.

According to the data and flight trajectory of a SoV, the status of the flight can be monitored by ground staff. If the vehicle's trajectory is abnormal, ground staff may be able to make trajectory adjustment or emergency recovery through telecommand. Additional trajectory measurement system(s) may be needed by the SoV throughout the phases of the flight.

5.1.4 Safety of life

Radiocommunication applications that provide a means of control to SoV during its flight (for example to avoid reaching populated or protected areas) are considered related to the safety of life, thus frequency bands used for safety of life purposes must be considered. It would be required to check with compatibility studies to verify this usage of these frequencies by SoV would not apply any additional constraints on existing systems operated in the same service or in other services.

5.2 Spectrum management aspects

Article **1** of the RR sets out the terms and definitions used within the RR. These include definitions of forty-two different radio services relating to *radiocommunication*. Radiocommunication is then further broken down into terrestrial radiocommunication, space radiocommunication and radio astronomy.

Based on these definitions, the radiocommunication services under which applications for SoV operates need to be analysed, e.g. terrestrial services, satellite services or new services which may depend on the phase of flight.

According to Article **1** of the RR any space station will use space radiocommunications. As a SoV follows a non-orbital trajectory it does not meet the definition contained in the RR for a satellite.

As a result, this leaves the following services applicable to space stations when not being considered a satellite*:* Space operation service, Space research service, and Mobile satellite service (in regard with the way the SoV is considered an earth station or a space station).

In Article **5** of the RR the allocations for the services listed above specify a direction of transmission such as space-Earth, Earth-space, and space-space. It is uncertain which transmission directions the SoV can use.

Equipment on-board space planes and SoV have been identified in Annex 2 that operate in frequency ranges that do not include the above radiocommunications services.

Furthermore, it is envisaged that for the purpose of flight under aeronautical regulation in upper atmosphere, the station on board SoV may also be considered as a terrestrial station or an earth station even if a part of the flight occurs in space.

6 Studies

The studies provided in Annex 3 and Annex 4 of this Report provide a Doppler shift and link budget analysis for current aeronautical systems that may be used on SoV. Annex 3 provides calculated values using the Doppler shift equation and free space path loss equation for terrestrial aeronautical systems. Annex 4 provides results from simulations for Doppler shift and link budget analysis and includes some aeronautical satellite systems.

Annex 5 provides studies into the SoV communications coverage requirements, the Doppler shift and Doppler acceleration, the conditions that could experience a communications blackout, and Spectrum selection criteria under those conditions.

Annex 1

Current methods for separating suborbital vehicle activities from air traffic

A1.1 Impact to air transportation

Below are current methods to reduce the size and time of temporary flight restrictions used to segregate airspace for launch and re-entry of SoV:

1) moving launch areas and re-entry zones away from air traffic areas;

2) minimizing the duration of the launch or re-entry operation’s window (i.e. the amount of time that airspace restrictions must be in place);

3) moving the operation window away from peak traffic times, or times when there will be air traffic within the area;

4) altering the launch or re-entry trajectory, to the extent possible, to avoid placing airspace restrictions in congested airspace;

5) coordinating with the using agencies of adjacent special use airspace to release their airspace during the operation, reducing reroute mileage of affected aircraft and alleviating choke points;

6) inserting corridors in an aircraft hazard area that allow aircraft to traverse the area in a controlled manner that does not exceed acceptable safety limits;

7) implementing a responsive approach to airspace management in which the ANSP and Regulator monitors a launch or re-entry operation in real-time and relies on a capability to compute and distribute a real-time aircraft hazard area to tactically respond to a contingency scenario rather than pre-emptively closing the airspace. This also includes using hotlines with the vehicle operator, ATC facilities, and other parties to expedite the direct communication of cancellations, delays, and contingencies.

An analysis of an individual launch and re-entry for one SoV is discussed further in this section. The flight restrictions due to a SoV launch and re-entry are provided in Figs A1-1 and A1-3, while current conditions for aircraft on similar launch days are provided in Figs A1-2 and A1-4. Table A1.1 provides the altitude and time for each temporary flight restriction (TFR). The SoV was launched 1st March 2013 and re-entered on 26th March 2013.

FIGURE A1-1

Suborbital vehicle launch from Florida, temporary restricted airspace, March 1st 2013

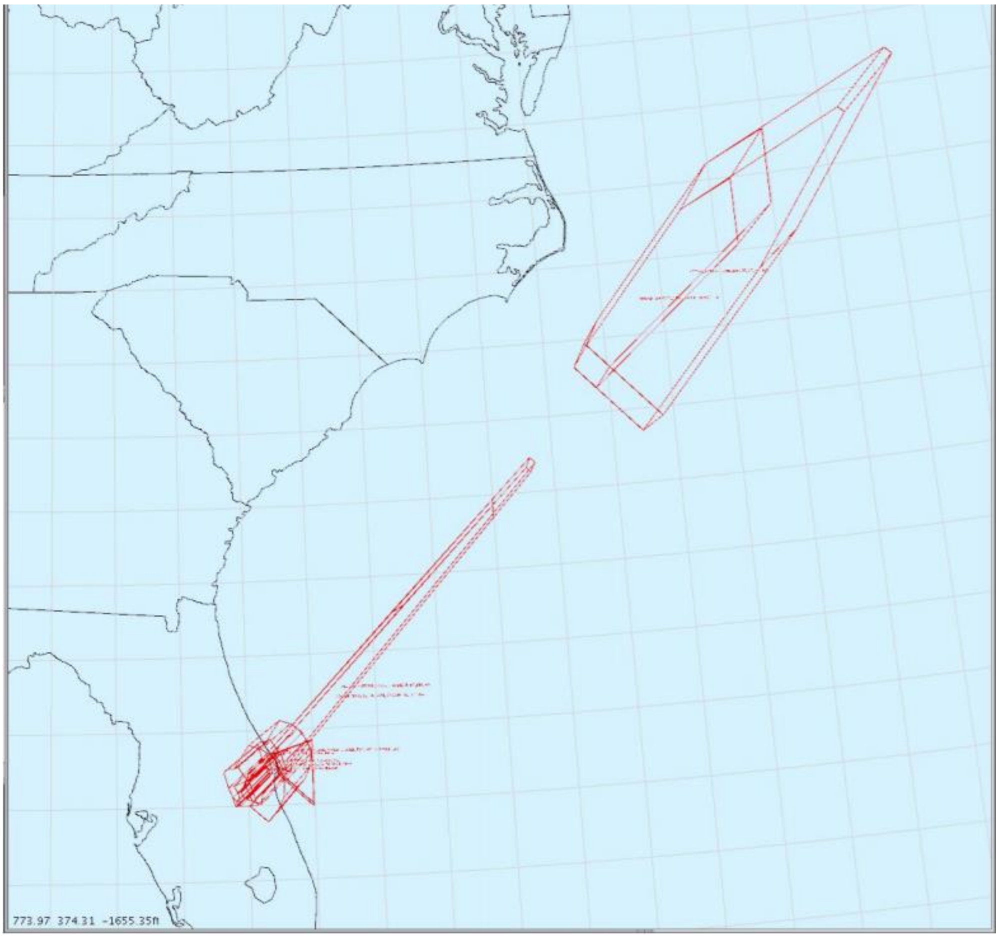


FIGURE A1-2

Typical flight paths on launch day

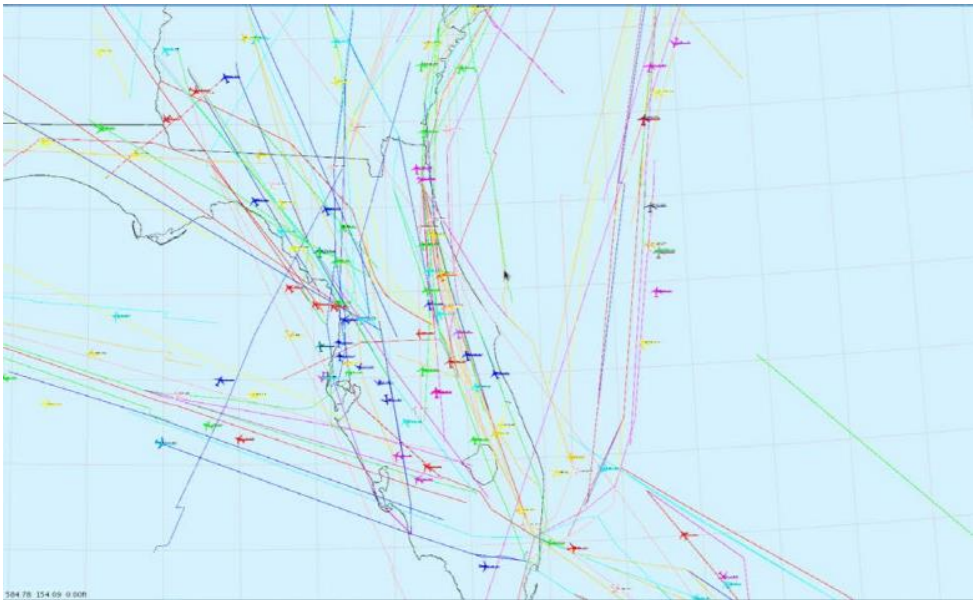


FIGURE A1-3

Suborbital vehicle re-entry in California, restricted airspace, March 26th 2013

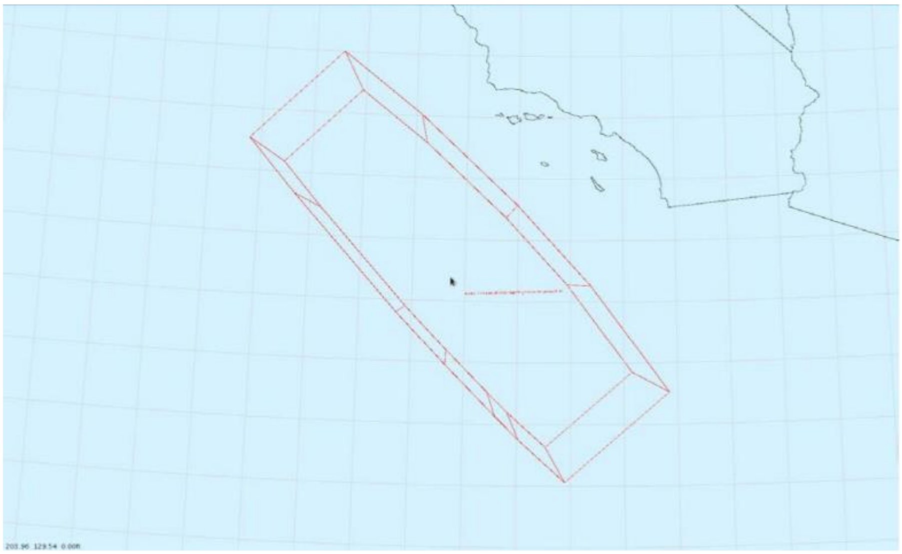


FIGURE A1-4

Suborbital vehicle re-entry in California, restricted airspace, March 26th 2013

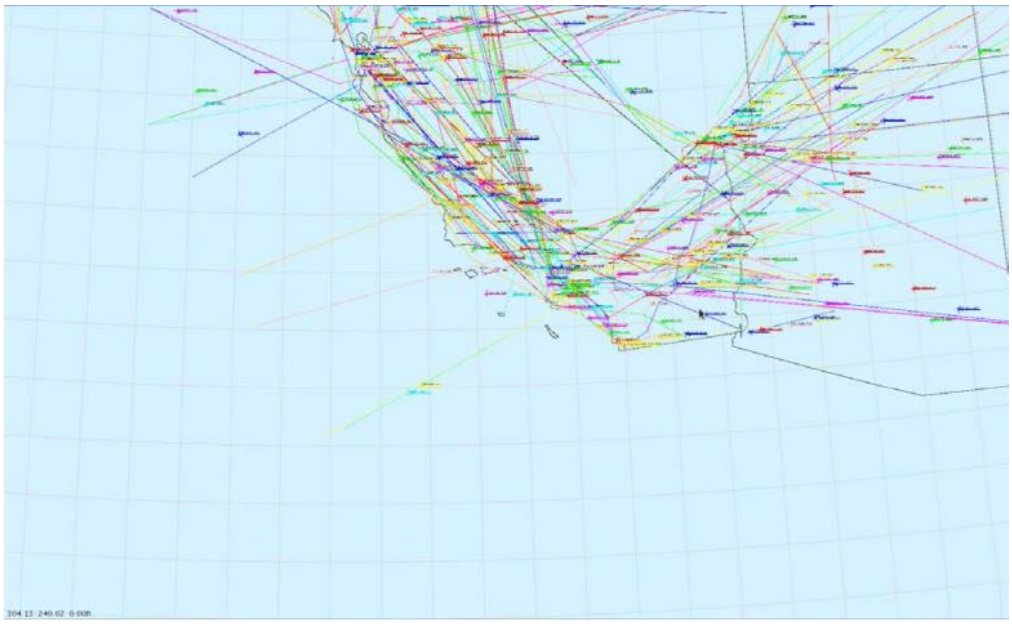


TABLE A1.1

Suborbital vehicle temporary flight restrictions time and altitude restrictions

Florida – Launch operation temporary flight restriction			
Launch temporary flight restriction name	**Altitude level restrictions (m)****	**Start time (Local)**	**End time (Local)**
W-497A_#1	SFC to 1 500	7:10 AM	10:43 AM
W-497A_Whole	SFC to 5 500	8:10 AM	10:10 AM
TFR_KSC	SFC to UNL	9:40 AM	10:43 AM
Downrange_AC_Hit_HA	SFC to UNL	10:10 AM	10:43 AM
First_Stage_Impact_HA	SFC to UNL	10:10 AM	10:43 AM
Launch_Danger_AC_Hit_HA	SFC to UNL	10:10 AM	10:43 AM
Launch_Danger_AC_Hit_WA	SFC to UNL	10:10 AM	10:43 AM
R-2933_Cape_Canaveral	SFC to UNL	10:10 AM	10:43 AM
R-2934_Cape_Canaveral#1	SFC to UNL	10:10 AM	10:43 AM
R-2934_Cape_Canaveral#2	SFC to UNL	10:10 AM	10:43 AM
California – Re-entry operation temporary flight restriction			
Re-entry temporary flight restriction name	**Altitude level restrictions (m)**	**Start time (Local)**	**End time (Local)**
ReEntry_Stationary_Reserve_HA	SFC to UNL	9:16 AM	9:43 AM
* SFC and UNL means surface and unlimited respectively.			

A1.2 Analysis of suborbital vehicle launch in March 2013

An impact analysis is provided below for four different area control centre (ACC). Two of the ACC are considered for launch ICAO location indicator KZJX (Jacksonville, FL, USA) and KZMA (Miami, FL, USA) and for the re-entry: KZOA (Oakland, CA, USA) and KZLA (Los Angeles, CA, USA). Both impact analyses involved comparing the flight distance, fuel burn, and duration of flights on the launch and re-entry days against similar flights on the five comparison days. For each day, these metrics were averaged over a pairing category which combined aircraft type, airline, and city pair (origin and destination airport pair). A matched pair analysis or paired t-test was conducted to determine the statistical significance of any differences between the days.

Results of the impact analyses are reported by the city pair type, defined as ‘primary’ or ‘secondary’. Key city pairs were identified on the five comparison days. This helped to derive a set of city pairs that would have flight paths directly impacted by the space operations (these are referred to as ‘primary’ city pairs).

ACC traffic data from the launch and re-entry days was calculated for each flight the closest point to each TFR polygon. A negative distance indicated that the flight entered the TFR. Before calculating the average distance from each TFR, flights with a closest point greater than 50 nautical miles (NM) from a TFR were excluded from the analysis. The calculation was performed for every flight in the ACC, including those never within proximity of the SoV.

A1.2.1 Assumptions and limitations

The following list addresses some assumptions and limitations acknowledged throughout this study:

- The five comparison days were chosen to minimize the differences in weather constraints from the launch and re-entry days. A difference in flight schedules may exist since the comparison days were not the same weekday and the launch and re-entry days. This may cause some variation seen in the comparison results;
- The number of flights used in the analysis was limited due to partial flight data and merging errors. Gaps in the recorded data caused most of these errors. A sufficient sample of flights remained in the analysis to allow researchers to form conclusions based on the results;
- This analysis was based on comparing the flight profiles of similar flights, where similar was defined as sharing the same aircraft type, airline, origin airport, and destination airport;
- The difference in flight distance, duration and fuel burn is assumed to be due to the SoV operation. Variables such as wind and day of week can significantly change a flight path, but it was not accounted for in this study;
- Only flights flying through the Florida and California ACCs were used in this study. It was assumed that these flights experienced the largest impact from the SoV because of prevailing flight paths;
- The operational analysis focused on flights flying within 50 NM of the TFR. These flights were assumed to experience the largest impact from the commercial 20 space operation. Flights that did not fly within 50 NM of the TFR were excluded from the analysis.

A1.2.2 Impact of launch operations

In order to assess the impact of the launch operation on KZJX and KZMA, several matched pair analyses were completed. This statistical test compared the average flight distance, fuel burn and flight duration for each city pair type on the launch day against the same metrics on the five comparison days. The pairing categories associated with the launch ACCs were grouped into two city pair types: primary and secondary. The “primary” city pairs were those with a flight path that would have entered the launch TFR. The “secondary” city pair category captured domestic and international flights not expected to have a flight path that would enter the TFR.

The summary of results for each metric can be found in Tables A1.2 through A1.4. A positive mean difference indicates the average added distance and time flown and extra fuel burned by flights on the launch day.

TABLE A1.2

Flight distance matched pair analysis for launch

Flight distance analyses	Number of flights	Mean difference (NM)	Standard error (NM)	P-value[1]	Significant (P_value less than or equal to 0.05)
03/01 – 02/28 (Primary)	9	35.7957	6.4066	0.0003	Yes
03/01 – 02/28 (Secondary)	234	25.3755	1.86	0.0001	Yes
03/01 – 03/02 (Primary)	11	50.1063	17.3919	0.0082	Yes

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[1] P_value is a statistical measurement when testing a hypothesis about a population.

TABLE A1.2 (*end*)

Flight distance analyses	**Number of flights**	**Mean difference (NM)**	**Standard error (NM)**	**P-value[2]**	**Significant (P_value less than or equal to 0.05)**
03/01 – 03/02 (Secondary)	213	24.9962	2.0291	0.0001	Yes
03/01 – 03/03 (Primary)	10	84.1118	25.0905	0.0042	Yes
03/01 – 03/03 (Secondary)	206	27.8795	1.9297	0.0001	Yes
03/01 – 03/07 (Primary)	8	29.9077	12.4974	0.024	Yes
03/01 – 03/07 (Secondary)	236	25.2494	1.9309	0.0001	Yes
03/01 – 03/27 (Primary)	10	32.4967	12.781	0.0158	Yes
03/01 – 03/27 (Secondary)	201	24.7027	2.159	0.0001	Yes

TABLE A1.3

Fuel burn matched pair analysis for launch

Flight fuel burn analyses	**Number of flights**	**Mean difference (kg)**	**Standard error (kg)**	**P-value**	**Significant (P_value less than or equal to 0.05)**
03/01 – 02/28 (Primary)	9	530.87	264.82	0.04	Yes
03/01 – 02/28 (Secondary)	234	124.66	26.25	0.0001	Yes
03/01 – 03/02 (Primary)	11	44.73	290.39	0.4403	No
03/01 – 03/02 (Secondary)	213	138.25	26.64	0.0001	Yes
03/01 – 03/03 (Primary)	10	1007.48	239.83	0.0012	Yes
03/01 – 03/03 (Secondary)	206	170.45	42.9	0.0001	Yes
03/01 – 03/07 (Primary)	8	1069.38	228.2	0.0011	Yes
03/01 – 03/07 (Secondary)	236	191.41	37.74	0.0001	Yes
03/01 – 03/27 (Primary)	10	1082.62	328.67	0.0047	Yes
03/01 – 03/27 (Secondary)	201	165.87	36.54	0.0001	Yes

---

[2] P_value is a statistical measurement when testing a hypothesis about a population.

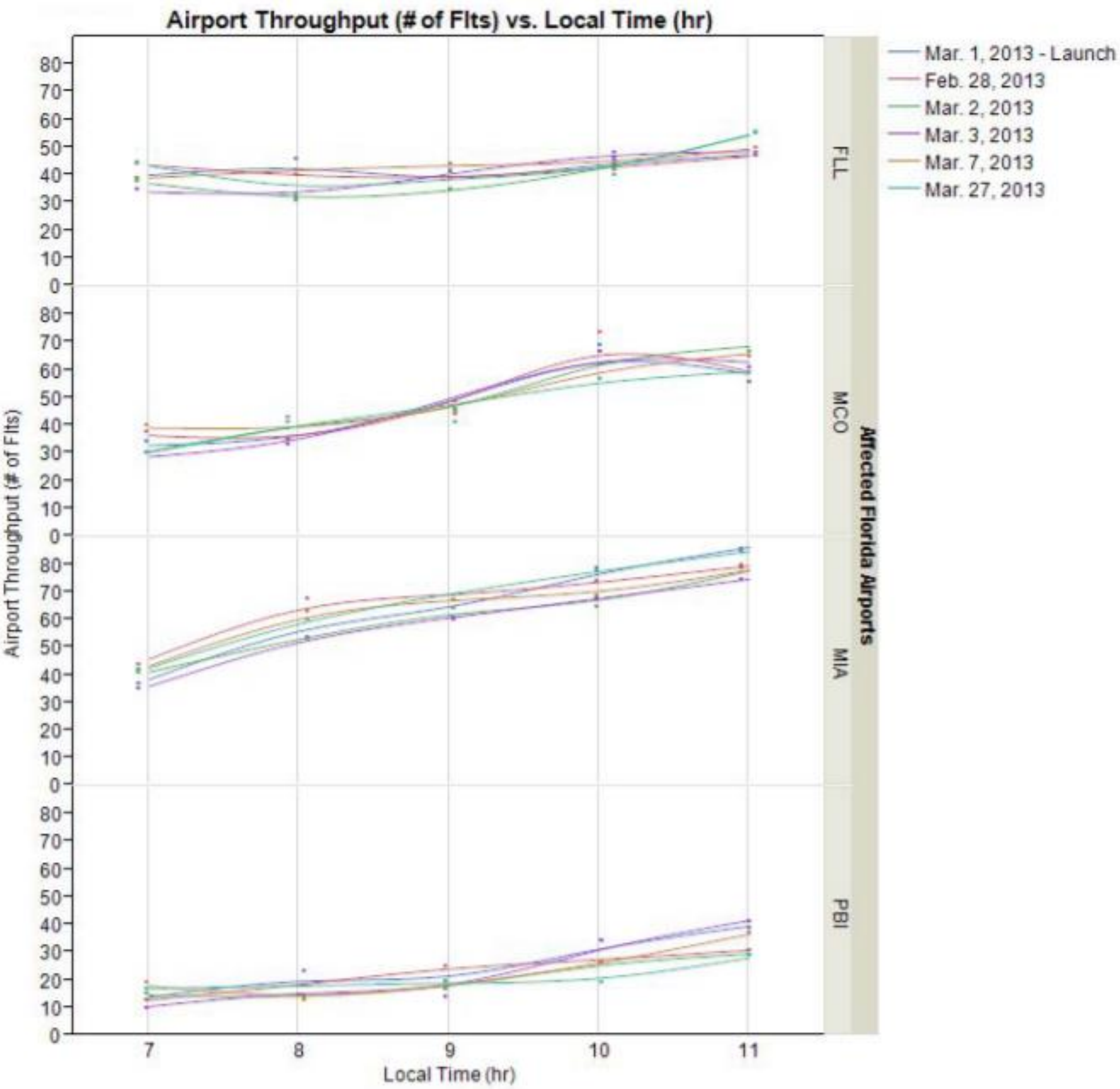
TABLE A1.4

Flight duration matched pair analysis for launch

Flight duration analyses	Number of flights	Mean difference (sec)	Standard error (sec)	P-value	Significant (P_value less than or equal to 0.05)
03/01 – 02/28 (Primary)	9	419.2220	109.7370	0.0025	Yes
03/01 – 02/28 (Secondary)	234	43.0519	29.4818	0.0728	No
03/01 – 03/02 (Primary)	11	20.2273	183.1530	0.4571	No
03/01 – 03/02 (Secondary)	213	66.2854	30.9750	0.0168	Yes
03/01 – 03/03 (Primary)	10	1400.6400	264.8930	0.0003	Yes
03/01 – 03/03 (Secondary)	206	169.6340	52.8204	0.0008	Yes
03/01 – 03/07 (Primary)	8	1319.5800	259.4370	0.0007	Yes
03/01 – 03/07 (Secondary)	236	53.0191	52.6931	0.1577	No
03/01 – 03/27 (Primary)	10	943.4580	184.3930	0.0003	Yes
03/01 – 03/27 (Secondary)	201	29.9282	42.2742	0.2399	No

FIGURE A1-5

Florida airport throughput by day analysis



A1.3 Summary of launch operations impact

Overall results of the matched pair analysis suggest that flights traversing through both the KZJX and KZMA ACCs experience significant impacts in terms of flight distance, total fuel burn, and flight duration. Nearly all of the comparisons indicated significant differences in all three metrics. Interestingly, all city pairs (primary and secondary) experienced significantly larger flight distances and fuel burn on the launch day. While some variables such as wind may have caused some differences in the flights among the days, this unexpected result could also indicate that the rerouted flight paths of the primary flights have a significant impact on secondary flights in the Florida airspaces.

Given the relatively few insignificant differences found in this analysis, it could be concluded that the SoV launch operation significantly impacted the flight distance, fuel burn, and duration of all flights in the Florida ACCs. The launch caused impacted flights to fly between 25 and 84 NM longer, burn between 125 and 1.083 kilograms more fuel, and fly for between 1 and 23 minutes longer as compared to days with no launch activity

Four airports were considered that may have been affected by the SoV launch given their proximity to the launch site. These airports are Fort Lauderdale-Hollywood International (KFLL), Orlando International (KMCO), Miami International (KMIA), and Palm Beach International (KPBI). A comparison was done for the number of hourly operations at each of these airports over the launch and comparison days. The hours between 7:00 am EST and 11:00 am EST are included in this analysis since they encompass the activation times of the TFRs. Figure A1-5 depicts the hourly throughput for this time period. It appears that the total number of hourly operations at each airport varies even among the comparison days, and the total number of hourly operations on the launch day is within this variation; therefore, no significant impact to total hourly operations was experienced on the launch day.

A1.4 Impact of re-entry operations

For this analysis, all five comparison days were compared against the re-entry day, March 26, 2013, using a matched pair analysis. Similar to the launch analysis, the pairing categories associated with the ACCs were grouped into city pair types. The ‘Primary’ city pairs were those with a flight path that would have entered the re-entry TFR. Other flights were categorized as ‘Secondary Domestic’ and ‘Secondary International (Int’l)’ in order to explore a possible impact to international flights traveling between some airports and California. Though they were not identified, these city pairs could be affected by the SoV re-entry since wind conditions sometimes require their flight paths to enter the TFR.

Results indicate that, in most comparisons, the re-entry operations did not cause a significant increase in flight distance, fuel burn and flight duration. However, some of the metrics were significantly different for a few of the comparison days and city pair types.

Pacific flights during the re-entry operation had significantly higher flight distance, duration, and fuel burned when compared against similar flights on March 7, 2013 and March 27, 2013; these flights also burned significantly more fuel on the re-entry day than on February 28, 2013. Other international flights on the re-entry day burned significantly more fuel and flew significantly longer than similar flights on February 28, 2013 and March 2, 2013. Unexpectedly, domestic flights during the re-entry flew significantly longer than similar flights on February 28, 2013. Statistically significant impacted flights flew between 15 and 27 NM more, burned between 208 and 261 kg more fuel, and flew between 1.5 and 7 min longer to avoid the re-entry TFR.

Flight paths, especially for international flights, depend heavily on the wind direction and magnitude. Wind was not considered in this analysis; thus, it could account for the inconsistency in the comparisons and the range of mean differences.

TABLE A1.5

Flight distance matched pair analysis for re-entry

Flight distance analyses	Number of flights	Mean difference (NM)	Standard error (NM)	P-value	Significant (P_value less than or equal to 0.05)
03/26 – 02/28 (Domestic)	261	−6.4249	1.7576	0.9998	No
03/26 – 02/28 (Primary)	10	−0.8929	5.4109	0.5645	No
03/26 – 02/28 (Secondary Int’l)	17	5.6578	8.5213	0.2617	No
03/26 – 03/02 (Secondary Domestic)	245	0.8782	1.3922	0.2644	No
03/26 – 03/02 (Primary)	8	3.3196	7.1870	0.3247	No
03/26 – 03/02 (Secondary Int'l)	20	13.8646	13.0943	0.1624	No
03/26 – 03/02 (Secondary Domestic)	245	0.7807	1.7179	0.3250	No
03/26 – 03/02 (Primary)	8	−1.0111	7.3181	0.5542	No
03/26 – 03/02 (Secondary Int'l)	19	−10.3750	11.3671	0.8041	No
03/26 – 03/02 (Secondary Domestic)	282	−0.8039	503.098	0.0011	Yes
03/26 – 03/02 (Primary)	10	14.6077	8.0273	0.0423	Yes
03/26 – 03/02 (Secondary Int'l)	20	11.6641	9.1429	0.1170	No
03/26 – 03/02 (Secondary Domestic)	236	−2.3371	1.2413	0.9695	No
03/26 – 03/02 (Primary)	10	26.9594	8.4002	0.0034	Yes
03/26 – 03/02 (Secondary Int'l)	14	2.6362	4.5505	0.2883	No

TABLE A1.6

Fuel burn matched pair analysis for re-entry

Flight fuel burn analyses	**Number of flights**	**Mean difference (kg)**	**Standard error (kg)**	**P-value**	**Significant (P_value less than or equal to 0.05)**
03/26 – 02/28 (Domestic)	261	530.87	37.36	0.0624	No
03/26 – 02/28 (Primary)	10	236.3	71.27	0.0022	Yes
03/26 – 02/28 (Secondary Int’l)	17	217.99	101.78	0.0304	Yes
03/26 – 03/02 (Secondary Domestic)	245	−50.82	48.26	0.8533	No
03/26 – 03/02 (Primary)	8	246.7	126.32	0.0329	Yes
03/26 – 03/02 (Secondary Int'l)	20	261.66	77.86	0.0060	Yes
03/26 – 03/02 (Secondary Domestic)	245	32.45	29	0.1321	No
03/26 – 03/02 (Primary)	8	−106	118.46	0.8087	No
03/26 – 03/02 (Secondary Int'l)	19	−146.09	88.34	0.9289	No
03/26 – 03/02 (Secondary Domestic)	282	−14.85	25	0.0011	Yes
03/26 – 03/02 (Primary)	10	207.9	115.46	0.0438	Yes
03/26 – 03/02 (Secondary Int'l)	20	−303.14	112.36	0.9878	No
03/26 – 03/02 (Secondary Domestic)	236	−36.42	22.52	0.9464	No
03/26 – 03/02 (Primary)	10	234.75	101.95	0.0209	Yes
03/26 – 03/02 (Secondary Int'l)	14	−5.23	53.63	0.5378	No

TABLE A1.7

Flight duration matched pair analysis for re-entry

Flight duration analyses	**Number of flights**	**Mean difference (sec)**	**Standard error (sec)**	**P-value**	**Significant (P_value less than or equal to 0.05)**
03/26 – 02/28 (Domestic)	261	92.7790	47.1092	0.0250	Yes
03/26 – 02/28 (Primary)	10	80.3333	65.5615	0.1191	No
03/26 – 02/28 (Secondary Int’l)	17	417.8000	155.0320	0.0123	Yes
03/26 – 03/02 (Secondary Domestic)	245	44.4171	51.2481	0.1935	No
03/26 – 03/02 (Primary)	8	112.7750	81.1808	0.0904	No
03/26 – 03/02 (Secondary Int'l)	20	437.3750	121.4040	0.0044	Yes

TABLE A1.7 (*end*)

Flight duration analyses	**Number of flights**	**Mean difference (sec)**	**Standard error (sec)**	**P-value**	**Significant (P_value less than or equal to 0.05)**
03/26 – 03/02 (Secondary Domestic)	245	9.9315	29.8335	0.3697	No
03/26 – 03/02 (Primary)	8	−146.8200	80.1681	0.9582	No
03/26 – 03/02 (Secondary Int'l)	19	−237.2300	148.9020	0.9224	No
03/26 – 03/02 (Secondary Domestic)	282	−20.4410	24.3749	0.7988	No
03/26 – 03/02 (Primary)	10	147.7750	78.1022	0.0369	Yes
03/26 – 03/02 (Secondary Int'l)	20	−421.9500	207.8660	0.9635	No
03/26 – 03/02 (Secondary Domestic)	236	−107.6300	78.0503	0.9154	No
03/26 – 03/02 (Primary)	10	315.1430	77.9146	0.0007	Yes
03/26 – 03/02 (Secondary Int'l)	14	−32.6000	102.6830	0.6209	No

A1.5 Conclusion of suborbital launch case study for March 2013

As demonstrated in the study, SoV launches and re-entry have an impact on both international and domestic air traffic. A difficulty highlighted in this study is the effect of wind on determining if international traffic routes fall within or near the temporary flight restrictions for SoV. When examining the impact of SoV, it should be noted that in cases of international traffic, indirect impacts from rerouting of domestic flights will also impact international flight. While this case provides a good example, it cannot conclusively determine the overall impact of SoV launches on air transportation. In addition, this only considers an individual mission type, and does not encompass all missions.

Annex 2

Possible radiocommunication services use for suborbital vehicle flight operations

A2.1 Services that may be used for the operation of suborbital vehicles

Examples of radiocommunication services that could be used to support the operation of SoV is given in Table A2.1, however it’s not clear that all of these services may be required in all phases of flight or in all administrations. It is also unclear if all of these systems are permitted by the RR to be used in space or if the sub-orbital vehicles are considered to be a space station when in space.

TABLE A2.1

Possible radiocommunication services used during suborbital flight to support the operation of the suborbital vehicle

Radiocommunication service	**Operational uses**	**Examples of internationally standardized aeronautical systems that might be extended for suborbital vehicle applications**
Aeronautical radionavigation service	Surveillance Navigation	SSR, Airborne collision avoidance system DME Microwave landing system/Instrument landing system Radio Altimeter
Aeronautical mobile service	Communication Surveillance	HF/VHF ATC ADS-B
Aeronautical mobile satellite service	Communication Surveillance	ADS-B Automatic dependent surveillance-contract(ADS-C) Controller-pilot data link communications
Mobile satellite service	Communication Telemetry, tracking, and command	
Aeronautical radiodetermination service	Surveillance	
Radionavigation-satellite service	Navigation	GNSS
Space operation service	Telemetry, tracking, and command	

Annex 3

Terrestrial aeronautical systems – potential issues

This Annex provides an analysis of the capability of some existing terrestrial aeronautical systems to operate, despite the Doppler effect, when those stations are onboard SoV. This Annex does not address any impacts of those systems on any other radiocommunication services.

A3.1 Overview

Current terrestrial aeronautical systems are designed to support aircraft flying at altitudes generally below 60 000 ft (18 288 m) and at sub-sonic speeds, although there have been exceptions such as Concorde which have been accommodated. SoV however, are intended to fly at greater altitudes and faster speeds as illustrated in Table A3.1.

TABLE A3.1

Suborbital vehicle compared to conventional aircraft key parameters

	Units	**Typical large commercial aircraft**	**Concorde**	**Typical suborbital vehicle**
Velocity	NM/h (km/h)	515 (954)	1 177 (2 179)	3 510 (6 500)
Altitude	Ft (m)	45 000 (13 716)	60 000 (18 288)	393 700 (120 000)

Those differences will increase Doppler shift effects and may require changes to link budgets (to accommodate greater ranges) and changes to planning rules (to accommodate the increased radio horizon distance associated with a SoV compared with conventional aircraft). The analysis carried out in this section into whether the impact of these effects could be accommodated by existing terrestrial aeronautical systems is based on current ICAO equipment standards and recommended practices/industry minimum operational performance standards, from which the following parameters have been extracted/derived.

TABLE A3.2

Terrestrial aeronautical system parameters

		Frequency band	**Typical transmitted power**	**Frequency tolerance**	**Minimum receiver sensitivity(1)**
		(MHz)	**(dBW)**	**(kHz)**	**(dBm)**
VHF communications	air to ground	117.975-137	14(2)	3.8 (25 kHz) 0.635 (8.33 kHz)	–93(2)
	ground to air		20(2)		–89.7(2)
Automatic dependent surveillance – broadcast	air to ground	1 090	21	1 000	–84
Distance measuring equipment	air to ground	960-1 215	24	100	–95.1
	ground to air		36	21.8	–83

(1) These values are the minimum required in standards however in practice equipment may be more sensitive which would improve the link budgets.

(2) These values are specified as needing to be achieved ‘on a high percentage of occasions’, however what this means is not defined and hence for the purposes of this analysis free space path loss is assumed with no statistical variation applied.

A3.2 Doppler shift

A SoV reaches a typical maximum speed of about 3 510 NM/h (6 500 km/h) or 1 806 m/s at the apex of ascent and continues at that speed until it starts re-entry into the Earth’s atmosphere. In the worst case that velocity will be either directly away from or towards a stationary ground station providing the aeronautical service. If it is assumed that the maximum velocity away from the ground station is equal to that towards the ground station the maximum Doppler shift will be symmetrical about zero. Therefore, it does not matter whether the formula for the object moving towards or away from the ground station is used.

Doppler shift for an object moving towards the ground station can be calculated using the following formula:

$$f' = \frac{v}{(v - v_s)} . f - f$$

where:

f' = Doppler frequency

f = real frequency

v = velocity of light

v_s = velocity of the source.

Applying this formula to the various systems in Table A3.2 gives the following results for maximum Doppler shift:

–	VHF communication	765 Hz
–	ADS-B (1 090 MHz extended squitter)	6.56 kHz
–	DME	6.56 kHz

Comparing the results with the frequency tolerance required by the ICAO standards and recommended practices the Doppler shift should not cause a practical issue except for 8.33 kHz spacing for VHF communication where the Doppler shift exceeds the frequency tolerance.

A3.3 Link budget

Current link budgets are based on being able to establish radiocommunication between an aircraft flying within a given coordinated service area and a ground station designated to service that area. In the extreme the aircraft would be flying at 45 000 ft (13 716 m) at a range of 261 NM (483.4 km) which equates to the radio horizon. However, at the altitudes SoV are intended to fly the radio horizon would be 668 NM (1 237 km) or approximately 2.5 the radio horizon range for current systems.

Based on free space path loss using parameters available in Table A3.2, the maximum range that could be achieved whilst maintaining conformance with the ICAO standards and recommended practices/industry minimum operating performance standards are given below:

–	VHF communication	air to ground	722 NM (1 337 km)
		ground to air	985 NM (1 825 km)
–	ADS-B (1090 MHz extended squitter)		67 NM (124 km)
–	DME	air to ground	340 NM (629 km)
		ground to air	336 NM (622 km).

Comparing these maximum ranges to the SoV radio horizon distance there should be no issue with VHF communication. However, the ranges for both distance measuring equipment (DME) and especially ADS-B systems would be a limiting factor that would need to be addressed by increasing the transmit power, receiver sensitivity or both (noting that in practice equipment may be more sensitive than the figures used in these calculations), but care would need to be exercised to ensure that such changes would not affect the performance of the overall system.

NOTE – This assumes free space path loss, but it should be noted that the space shuttle experienced a communication blackout in the vehicle-to-ground direct path caused by ionisation of the envelope of air around the shuttle created by the heat from the compression of the atmosphere while the vehicle passed through the mesosphere on re-entry and hence free space path loss cannot necessarily be assumed. Given the presumed lower re-entry speeds of SoV the effects will be reduced but will need to be considered.

A3.4 Planning criteria

VHF communication: Currently VHF communication planning criteria for larger service volumes effectively aim to ensure that an aircraft is not in line of sight of two different service volumes using the same frequency. In Europe a maximum aircraft altitude of 45 000 ft (13 100 m) is assumed which results in the need for a minimum separation distance between the two service volumes on the same frequency of 522 NM (966 km). SoV however fly at altitudes of around 393 700 ft (120 000 m), which equates to a radio horizon distance of 668 NM (1 237 km), and so would not necessarily be protected from being in radio line of sight of more than one service volume. Therefore, if current VHF communication systems are to be used at such high altitudes, then there would be a need to revise the planning criteria, at least for those assignments used to support suborbital flight to take account of the increased radio horizon distances.

Automatic dependent surveillance-broadcast: ADS-B on 1 090 MHz uses a single global frequency and works on contention access with discrimination between signals based on received power and time. The capacity of the system is therefore limited by the length and repetition rate of a signal, the number of aircraft and the distribution of receivers and hence there are no frequency planning criteria considerations.

Distance measuring equipment: DME is a contention access system where an aircraft interrogates a ground transponder which then provides a reply with a given delay. In order to ensure a given quality of service the operational coverage volumes are planned in such a way as to ensure that an aircraft operating within that coverage volume will not be in radio line of sight of another ground DME station on the same frequency and hence planning criteria are potentially an issue. Given that the link budget would allow for a service range greater than the currently assumed maximum radio horizon, like VHF communication there would a need to review the planning criteria.

Annex 4

Studies of the Doppler shift and link budgets for typical aircraft systems on suborbital vehicles

A4.1 Doppler study

The Doppler shift being evaluated in this study is the change in frequency observed in the reference frame of a receiver due to any relative motion between a transmitter and that receiver. Simulations are performed to obtain the amount of frequency shift experienced by SoV using (ATC) VHF communications, 978 MHz universal access transceiver (UAT) ADS-B, 1 090 MHz extended squitter (1090ES) ADS-B, the 1 030 MHz secondary surveillance radar (SSR)/ traffic alert and collision avoidance system (TCAS) interrogator frequency, and Global positioning system (GPS)/Galileo navigation system frequencies.

Table A4.1 shows the minimum velocity (km/h) required to reach a 100 km orbit and a 200 km orbit, as a function of launch trajectory angle. These minimum velocities are much smaller than the orbital velocity of 28 238 km/h for a 100 km orbit and 28 022 km/h for a 200 km orbit. This results in small Doppler shift than the Doppler shift of SoV traveling at the orbital velocity.

TABLE A4.1

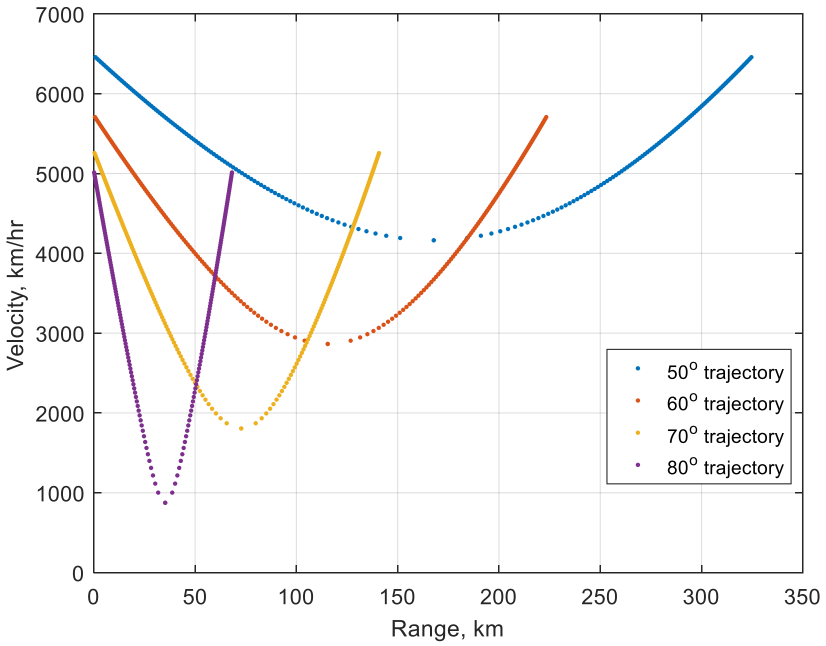
Minimum launch velocity required to reach orbits

Parameters	Minimum launch velocity required to reach 100 km orbit (km/h)	Minimum launch velocity required to reach 200 km orbit (km/h)
50° launch trajectory	6 477	9 021
60° launch trajectory	5 729	7 979
70° launch trajectory	5 280	7 354
80° launch trajectory	5 038	7 017

Figure A4-1 shows that the launch velocities required to reach 100 km orbit for various launch trajectories decrease as the SoV climbs to the 100 km orbit (occur when velocity per trajectory is at minimum), then increase on the way down with no additional force/thrust after the initial velocities.

FIGURE A4-1

Suborbital vehicle launch velocity profile as a function of launch trajectories



A4.1.1 VHF communications

For SoV communicating with ground systems, the in-view max Doppler shift in Hz due to the relative motion between the SoV (traveling at the orbital velocity) and the ground station are simulated and are shown in Fig. A4-2 as functions of ground station locations (various latitudes from –89 to 89 degrees and fixed longitude at 0 degree), altitudes of SoV (100, 125, 150, 175 and 200 km), and frequency channel (123 MHz in this figure). Each of the dots in Fig. A4-2 represents the in-view max Doppler shift, obtained from 10 000 runs of different orbital parameters of the SoV with each run 24 hours in duration, 10 seconds time steps, and a 0 degrees elevation mask. From Fig. A4-2, the in-view maximum Doppler shift varies little as a function of latitudes –89 to 89 degrees.

FIGURE A4-2

Maximum in-view Doppler shift of a suborbital vehicle communicating with a ground station at 123 MHz

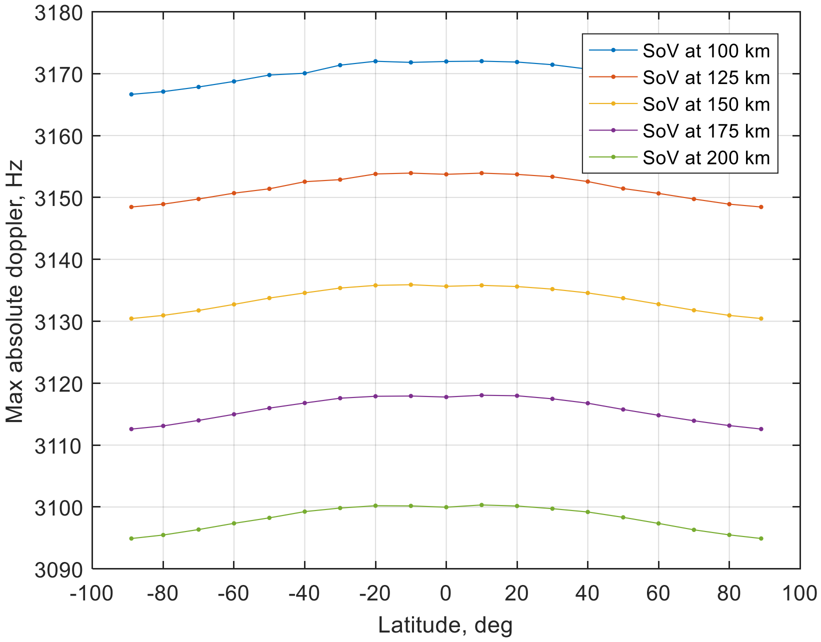


Figure A4-3 shows the maximum in-view Doppler shift of a SoV (traveling at the orbital velocity) communicating with VHF ground stations as functions of various frequency channels from 118 to 137 MHz and various altitudes. The max Doppler shift will be smaller when SoV travels at lower velocity than the orbital velocity.

FIGURE A4-3

Maximum in-view Doppler shift of a suborbital vehicle communicating with VHF ground stations from 118-137 MHz

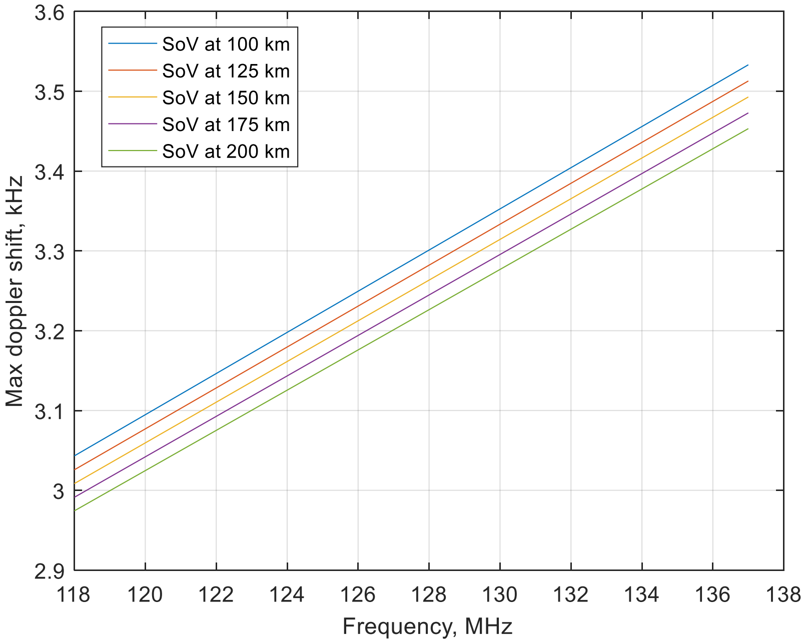


Table A4.2 shows the maximum in-view Doppler shift (SoV traveling at the orbital velocity) at 137 MHz as well as the maximum velocity for a SoV at 100, 125, 150, 175 and 200 km altitudes. The maximum Doppler shift will be smaller when SoV travels at lower velocity than the orbital velocity.

TABLE A4.2

Maximum in-view Doppler shift of a suborbital vehicle communicating with VHF ground station at 137 MHz

Altitudes (km)	**Max Doppler shift (kHz)**	**Max SoV velocity (km/h)**
100	3.5332	27,853
125	3.5129	27,693
150	3.4928	27,535
175	3.4729	27,378
200	3.4532	27,222

The VHF communications requirements are specified in Chapter 2 of Annex 10 to the Convention on International Civil Aviation Volume 3, Part II. As shown in Table A4.3, all the VHF communications equipment using 8.33 kHz channels and 25 kHz channels exceed the frequency tolerance when using on-board SoV operating above 100 km altitudes and traveling at the orbital velocity.

TABLE A4.3

Suborbital vehicle communicating at 137 MHz

	8.33 kHz VHF channels		**25 kHz VHF channels**	
Parameters	Ground Rx	SoV Rx	Ground Rx	SoV Rx
Transmitter frequency stability (Hz)	685 (5 ppm)	137 (1 ppm)	4 110 (30 ppm)	2 740 (20 ppm)
Receiver frequency stability (Hz)	137 (1 ppm)	685 (5 ppm)	137 (1 ppm)	685 (5 ppm)
Audio bandwidth (Hz)	350-2 400	350-2 400	350-2 400	350-2 400
Total frequency shift	1 172-3 222	1 172-3 222	4 597-6 647	3 775-5 825
Effective acceptance bandwidth (Hz)	3 462(1)	3 462(1)	6 850 (50 ppm)	6 850 (50 ppm)
Max frequency shift allowed (Hz)	240-2 290	240-2 290	203-2 253	1 025-3 075
Max SoV Doppler shift (Hz)	3 533	3 533	3 533	3 533
Exceedance (Yes/No)	Yes	Yes	Yes	Yes

(1) Annex 10 to the Convention on International Civil Aviation, Volume III, attachment to Part II, section 1.1.2: the effective acceptance bandwidth for 8.33 kHz equipment is required to be at least ±3 462 Hz.

However, from Table A4.1, the Doppler shift for SoV traveling at around 8 000 km/h (much less than the orbital velocity of 27 853 km/h) is around 1 015 Hz, which can be accommodated by the 25 kHz VHF channel radio on-board SoV (full 2 400 Hz audio bandwidth) and by the 25 kHz VHF channel radio on ground with some reduced audio bandwidth (1 588 Hz audio bandwidth).

The VHF communications equipment on SoV can be designed with tighter frequency stability (same as for 8.33 kHz VHF equipment). Table A4.4 shows that such VHF equipment can be used on SoV to communicate with the VHF ground stations.

TABLE A4.4

Suborbital vehicle communicating at 137 MHz

	25 kHz VHF channels	
Parameters	Ground Rx	Aircraft Rx
Tx frequency stability (Hz)	685 (5 ppm)	137 (1 ppm)
Rx frequency stability (Hz)	137 (1 ppm)	685 (5 ppm)
Audio bandwidth (Hz)	350-2 400	350-2 400
Total frequency shift (Hz)	1 172-3 222	1 172-3 222
Effective acceptance (Hz)	6 850 (50 ppm)	6 850 (50 ppm)
Max frequency shift allowed (Hz)	3 628-5 678	3 628-5 678
Max SoV Doppler shift (Hz)	3 553	3 553
Exceedance (Yes/No)	No	No

A4.1.2 Global navigation satellite, satellite communication (including the mobile satellite service, and the aeronautical mobile satellite (R) service) and aeronautical surveillance systems

For SoV navigating with the global navigation satellite service (GNSS) systems, for example GPS, Globalnaya navigatsionnaya sputnikovaya sistema (GLONASS), Beidou, and Galileo in this study, the maximum Doppler shift in Hz due to the relative motion between the SoV and the GNSS satellites are simulated and are shown in Fig. A4-4. Each of the dots in the Figure represents the max in-view Doppler shift, obtained from 10 000 runs of different orbital parameters of the SoV and GNSS orbital parameters (GPS with fixed inclination angle of 55 degrees and fixed satellite radius of 26 559.7 km; Galileo with fixed inclination angle of 56 degrees and fixed satellite radius of 29 600 km; GLONASS with fixed inclination of 64.8 degrees and satellite radius of 25 478 km; Beidou with fixed inclination angle of 55 degrees and fixed satellite radius of 27 878 km), each run of 24 hours in 10 seconds time steps, and a 0 degree elevation mask. The GNSS frequencies are as follows: GPS (L1, L2, L5), GLONASS (L1, L2, L3), Beidou (B1, B2, B3), and Galileo (E1, E5, E6).

Additionally, the maximum in-view Doppler shift using ADS-B on UAT, 1090ES/SSR transponder transmitter, the SSR/TCAS interrogator frequency, geostationary L-band satellite communication (R) in 1 525-1 559 MHz, and geostationary, and non-geostationary L-band satellite communication (T) in 1 626.5-1 660.5 MHz, and 1 616-1 626.5 MHz, respectively are also shown in Fig. A4-4.

FIGURE A4-4

Maximum in-view Doppler shift of a suborbital vehicle

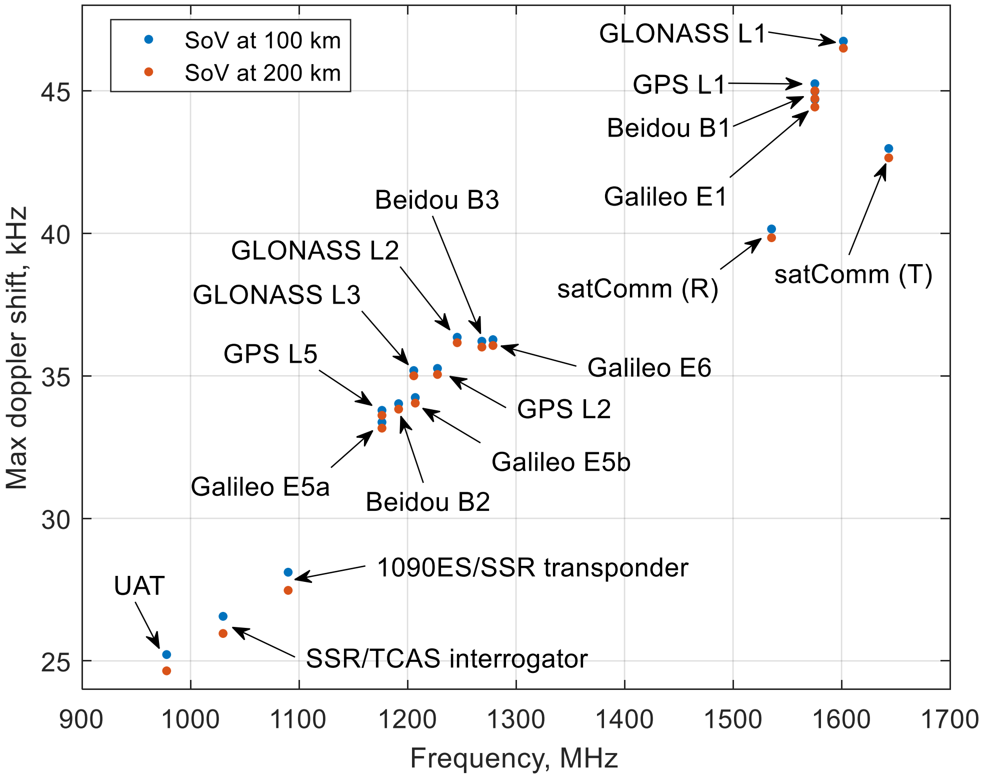


Table A4.5 shows the maximum in-view Doppler shift in Fig. A4-4 for each system proposed to be used by a SoV. Table A4.5 demonstrates an upper bound for the Doppler shift of the listed aviation systems.

TABLE A4.5

Maximum in-view Doppler shift of a suborbital vehicle

Aviation systems	Max. Doppler shift (kHz)	Max. relative SoV velocity (km/h)
UAT	25.222	27,853
SSR/TCAS Interrogator	26.563	27,853
1090ES/SSR transponder	28.110	27,853
Galileo E5a	33.373	30,638
GPS L5	33.789	31,021
Beidou B2	34.023	30,831
Galileo E5b	34.239	30,638
GLONASS L3	35.185	31,515
GPS L2	35.260	31,021
Beidou B3	36.213	30,831
Galileo E6	36.269	30,638
GLONASS L2	36.353	31,515
Galileo E1	44.692	30,638

TABLE A4.5 (*end*)

Aviation systems	**Max. Doppler shift (kHz)**	**Max. relative SoV velocity (km/h)**
Beidou B1	44.974	30,831
GPS L1	45.247	31,021
GLONASS L1	46.739	31,515
L-band SatComm (R)	40.151	28,240
L-band SatComm (T)	42.974	28,240

GPS and GNSS receivers normally employ a carrier tracking loop with a 10 Hz loop bandwidth and carrier numerically controlled oscillators (NCO)s of 5 to 40 MHz with sufficient number of quantized bits to meet the desired frequency output resolution to track the ~5 kHz Doppler shift. The max range of the NCO is half of the clocking rate (5 MHz) or 2.5 MHz. So, it can easily accommodate the SoV max GPS/GNSS Doppler shift of 45 kHz.

UAT is a broadcast data link operating on 978 MHz, with a modulation rate of 1.041667 Mbps. The example in Table A4.6, shows that a UAT aircraft receiver can tolerate the SoV traveling at the launch velocity or higher, but it cannot tolerate the SoV traveling at the orbital velocity if a ground receiver is intended to receive the messages.

TABLE A4.6

Universal access transceiver frequency tolerance for suborbital vehicles

Parameters	**Aircraft/Ground Rx(1) (UAT ground uplink msg)**	**Aircraft/Ground Rx(2) (Long/Basic UAT ADS-B msg)**
Nominal Tx frequency stability (kHz)	0.978 (1 ppm)	0.978 (1 ppm)
Nominal FM deviation (kHz)	625	625
Max Doppler shift (SoV at orbital velocity) /Max Doppler shift (SoV at min velocity required to reach orbit(3)) (kHz)	25.222 / 8.169	25.222 / 8.169
Total frequency shift (kHz)	651.2 / 634.147	651.2 / 634.147
Max frequency tolerance (kHz)	645.987	646.575
Exceedance (kHz)	5.213 / –11.84	4.625 / –12.428

(1) Annex 10 to the Convention on International Civil Aviation Volume III, section 12.3.2.1.3. a): max frequency tolerance = 625 (FM deviation) + 19.56 (max signal frequency offsets, 20 ppm) + 1.427 (850 knots) = 645.987 kHz.

(2) Annex 10 to the Convention on International Civil Aviation, Volume III, sections 12.3.2.1.1. a) & 12.3.2.1.2. a): max frequency tolerance = 625 (FM deviation) + 19.56 (max signal frequency offsets, 20 ppm) + 2.015 (1 200 knots) = 646.575 kHz.

(3) Per Table A4-1: Doppler shift for launch velocity required to reach 200 km orbit with 50° launch trajectory = 8.169 kHz.

As shown in Table A4.7, the 1090ES/SSR transponder can tolerate the SoV traveling at the orbital velocity. The SSR/TCAS interrogator function may be able to tolerate the SoV traveling at the orbital velocity since the ICAO Standard, Annex 10 to the Convention on International Civil Aviation, Volume IV, section 3.1.2.1.1, permits the tolerance during the phase reversal to be several MHz. Further investigation would need to be made if the SSR/TCAS interrogator functions are desired.

TABLE A4.7

Frequency tolerance of secondary surveillance radar/traffic alert and collision avoidance system interrogator and 1 090 extended squitter/secondary surveillance radar transponder for suborbital vehicles

Parameters	SSR/TCAS interrogator	1 090 ES/SSR transponder
Carrier frequency (MHz)	1 030	1 090
Frequency tolerance (kHz)	10(1)	1 000(3)
Max Doppler shift (SoV at orbital velocity) (kHz)	26.563	28.11
Exceedance (kHz)	(2)	No

(1) Annex 10 to the Convention on International Civil Aviation , Volume IV, section 3.1.2.1.1: the carrier frequency of all interrogations (uplink transmissions) from ground facilities with Mode S capabilities shall be 1 030 ± 0.01 MHz, except during the phase reversal, while maintaining the spectrum requirements of 3.1.2.1.2.

(2) Annex 10 to the Convention on International Civil Aviation, Volume IV, section 3.1.1.1.2: the frequency tolerance shall be ±0.2 MHz.

(3) Annex 10 to the Convention on International Civil Aviation , Volume IV, section 3.1.2.2.1: the carrier frequency of all replies (downlink transmissions) from transponders with Mode S capabilities shall be 1 090 ± 1 MHz.

A4.2 Link budgets

A4.2.1 VHF communications

Table A4.8 shows the link budget for the SoV with the slant range of 600 km (7 degrees elevation of the SoV at 100 km altitude). Most airborne VHF radios have an output power capacity of 30 Watts. Most ground VHF stations have antennas that can handle 100 Watts max power.

TABLE A4.8

VHF link budget for suborbital vehicles slant range of 600 km

	VHF ground-to-air	VHF air-to-ground
Tx power (dBW)	20	14.77 (30 Watts)
Tx antenna gain (dBi)	–1	–1
Slant range (km)	600	600
pfd reduction for 600 km (dBW/m^2)	126.6	126.6
Rx antenna gain (dBi)	–1	–1
Rx power density (dBW/m^2)	–108.6	–113.8
Required Rx power density (dBW/m^2)	–109	–120
Margin (dB)	0.4	6.2

A4.2.2 L-band satellite communications

Tables A4.9 and A4.10 show the link budgets for the geostationary and non-geostationary L-band satellite communication signals.

TABLE A4.9

Link budget for geostationary L-band satellite communications

Parameters	Uplink	Downlink
Transmit frequency (MHz)	1 643.5	1 542.0
e.i.r.p. (dBW)	16.0	21.8
Path loss (dB)	188.9	188.5
User antenna elevation angle (degrees)	5	5
Mean atmospheric loss (dB)	0.4	0.4
User/satellite antenna gain to noise temperature (dB/K)	–11.5	–23
Received C/N_0 (dB-Hz)	43.6	38.5
Received C/N (dB-Hz)	11.1	8.5
C/N objective (dB-Hz)	3.5	3.5
C/N margin (dB)	7.6	5

TABLE A4.10

Link budget for non-geostationary orbit L-band satellite communications

Parameters	Uplink	Downlink
Transmit frequency (MHz)	1 621.0	1621.0
e.i.r.p. (dBW)	6.5	21.2
Path loss (dB)	154.5	154.5
User antenna elevation angle (degrees)	8	8
Mean atmospheric loss (dB)	0.3	0.3
User/satellite antenna gain to noise temperature (dB/K)	–11.5	–27.0
Received C/N_0 (dB-Hz)	68.6	68.0
Received C/N (dB-Hz)	23.2	22.6
C/N objective (dB-Hz)	9.8	11.3
C/N margin (dB)	13.4	10.3

A4.2.3 Surveillance systems

Table A4-11 shows the UAT link budget for the SoV. The max e.i.r.p. for either UAT aircraft or ground station shall not exceed +58 dBm per Annex 10, Volume III, section 12.1.2.3.2 to the Convention on International Civil Aviation. This max e.i.r.p. could result from the maximum allowable aircraft transmitter (+54 dBm at power measurement point at the end of the cable that attached to the antenna. The cable connecting the antenna to the UAT equipment is assumed to have 3 dB loss) with a maximum antenna gain of 4 dBi. Table A4.11 also includes the case of 0 dBi Rx antenna gain.

TABLE A4.11

Universal access transceiver link budget for suborbital vehicles

	UAT ground-to-air		UAT air-to-ground	
Tx power (dBW)	24	24	24	24
Tx antenna gain (dBi)	0	4	0	4
Slant range (km)	317	502	398	632
Spreading loss (dB/m^2)	–121	–125	–123	–127
Rx antenna gain (dBi)	0	0	0	0
Rx power density (dBW/m^2)	–97	–97	–99	–99
Required Rx power density at the power measurement point (dBW/m^2)	–97(1)	–97(1)	–99(2)	–99(2)
Margin (dB)	0	0	0	0

(1) Annex 10 to the Convention on International Civil Aviation, Volume III, section 12.2.1.1.1, including 3 dB for excess path loss over free-space propagation.

(2) Annex 10 to the Convention on International Civil Aviation, Volume III, section 12.3.1.1, including 3 dB for excess path loss over free-space propagation.

Spreading loss, dB/m^2 = 10 log(1/(4πR^2))

Table A4.12 shows the SSR/TCAS and 1090ES/SSR link budget for the SoV.

TABLE A4.12

Secondary surveillance radar/traffic alert and collision avoidance system and 1090 extended squitter/secondary surveillance radar link budget for suborbital vehicles

	SSR ground to air (1 030 MHz)	Traffic information system-broadcast 1090ES	ADS-B 1090ES Air-to-ground (class A3, B1)	ADS-B 1090ES Air-to-ground (class A3, B1)
Tx power (dBm)	60	57	57(1)	57(1)
Tx antenna gain (dBi)	24	0	0	0
Slant range (km)	2 000	220	220	310
Slant range pathloss (dB)	158.7	140	140	143
Rx antenna gain (dBi)	0	0	0	0
Rx power (dBm)	−74.8	−83	−83	−86
Required Rx power (dBm)	−77(2)	−84(3)	−84(3)	−87(3)
Margin (dB)	2.2	1.0	1.0	1.0

(1) Annex 10 to the Convention on International Civil Aviation, Volume IV, Chapter 5, Table 5-1 for airborne receivers, class A3 and Table 5-2 for airborne receivers, class B1.

(2) Annex 10 to the Convention on International Civil Aviation, Volume IV, Chapter 3, section 3.1.2.10.1 (−74 dBm ± 3 dB).

(3) Annex 10 to the Convention on International Civil Aviation, Volume IV, chapter 5, Table 5-3, airborne receivers, class A3: receiver minimum trigger threshold level = −84 dBm (and −87 dBm at 15% probability of reception).

Table A4.13 shows the link budget for the GPS L1 C/A, GPS L2C, and GPS L5 signals.

TABLE A4.13

Link budget for global positioning system L1 coarse/acquisition, L2C, and L5 frequencies

Units	**GPS L1 C/A**	**GPS L2C**	**GPS L5**
Rx carrier power at antenna (dBW)	−158.5	−160	−157
Antenna gain at 5 degrees (dBi)	−5.5	−5.5	−5.5
Rx implementation loss (dB)	2.5	2.0	2.0
Effective Rx carrier power (dBW)	−166.5	−167.5	−164.5
Required Rx carrier power (dBW)	−164	TBD	TBD
Margin (dB)	−2.5	TBD	TBD
GNSS inter/intra interference (dBW/Hz)	−202.3	−203.7	−211.6
External broadband interference (dBW/Hz)	−206.5	−201.5	−193.3
Thermal noise power, N_0 (dBW/Hz)	−201.5	−201.5	−200.0
Effective noise power (dBW/Hz)	−198.2	−197.4	−192.4
Effective C/N_0 (dB-Hz)	31.7	29.9	27.9

From Table A4.13, the min GPS L1 coarse/acquisition (C/A) received power is −166.5 dBW or −136.5 dBm. This minimum level of −136.5 dBm may not achieve the acceptable acquisition (required −134 dBm). So, the GPS L1 signal must be in the higher elevation angle than 5 degrees to achieve −134 dBm. Normally, GPS receivers acquire GPS L1 signals from satellites at higher elevation angles, then use the information data to acquire other GPS L1 signals at lower elevation angles.

A4.3 Summary

Preliminary study shows that ATC systems can be used onboard SoV for communication, navigation, and surveillance:

- ATC VHF radio (25 kHz channels) onboard SoV may be able to communicate with ATC VHF base stations for a max slant range of 600 km and a max velocity of 8 000 km/h;
- SoV can use GNSS systems for navigation;
- SoV can use UAT systems (398 km range) or ADS-B 1090ES air-to-ground (220 km range) for surveillance during launch and re-entry.

Annex 5

Suborbital flight phase and selection of radiocommunication spectrum

A5.1 Overview

Compared with traditional aircraft, the SoV has a range (aeronautics) and speed variance. The SoV has a range (aeronautics) of up to ten thousand kilometres and the speed variance of SoV may vary from zero to several kilometres per second. As a result, this causes a series of problems, including the whole-period communication coverage during the entire flight, the large Doppler frequency deviation dynamics and the radiocommunication blackout problem caused by re-entry hypersonic flights. The current avionics cannot fulfil these requirements. However, mitigations are available by selecting appropriate communication frequencies. For the purpose of this Annex, frequency bands mentioned consider the following frequency ranges.

L-band contains range from 1 to 2 GHz;

S-band contains a range from 2 to 4 GHz;

Ka-band contains range from 23-40 GHz.

A5.2 Suborbital vehicle communication coverage requirements

Commercial SoV flight trajectory varies, radio stations may have operating multimode communication systems. Due to the constraints of ground station antenna beam pattern and curvature of the earth, each ground station can only cover a portion of the flight trajectory. In order to fulfil the coverage requirement of SoV, existing aviation ground facilities are good choices for low speed aeronautical phases. During high-speed flight phase (commonly supersonic or hypersonic), to overcome the problems of radiocommunication blackout and flight dynamics that caused by high velocity, higher frequency ground stations along the route are needed, or it is necessary to deploy data relay satellites.

An example SoV flight trajectory is shown in Fig. A5-1; Fig. A5-2 shows the corresponding altitude vs. ground range; Fig. A5-3 shows communication coverage time durations for each ground station and geostationary orbit (GSO) Tracking and Data Relay Satellites (TDRS) along the whole flight path.

FIGURE A5-1

An example suborbital vehicle flight trajectory

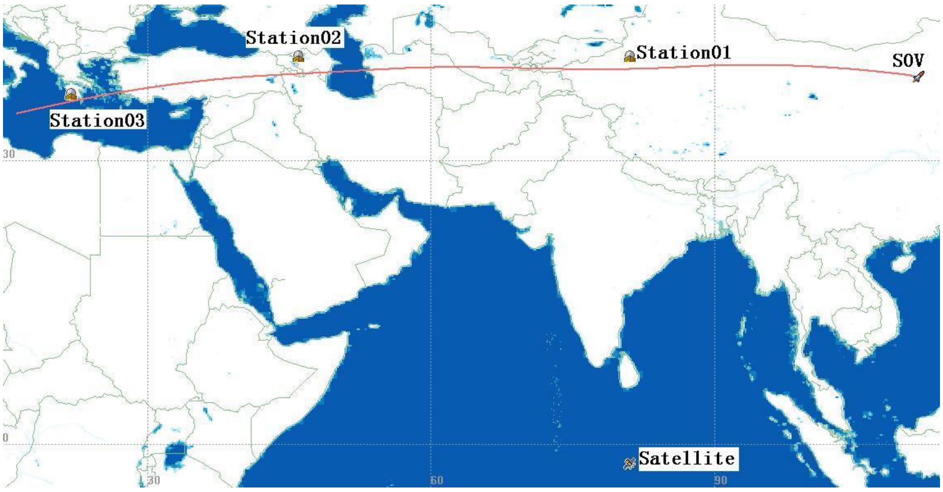


FIGURE A5-2

Trajectory profile

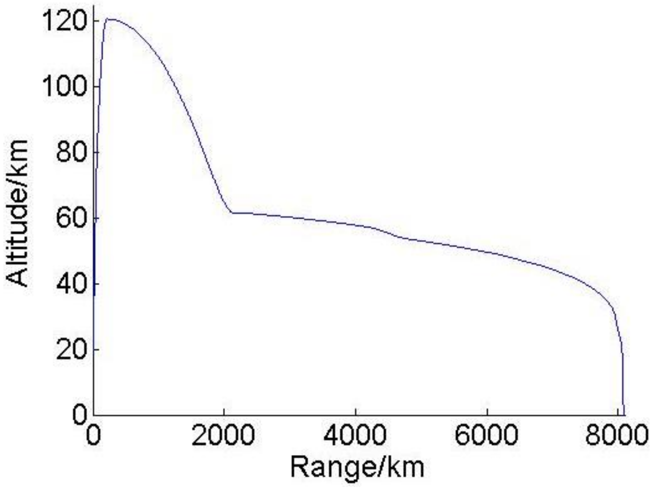
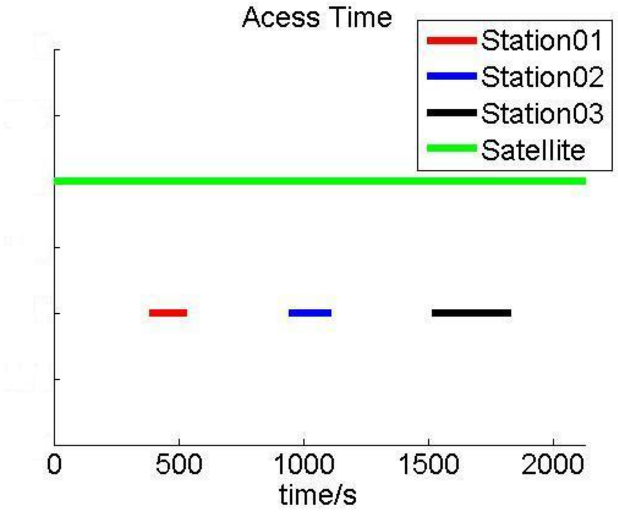


FIGURE A5-3

Communication coverage time duration



The current ground-based telemetry, tracking, and command stations and data relay satellites for high speed vehicles (such as spacecrafts, launch vehicles, space planes, etc.) work in the S or Ka band. To utilize existing stations, the SoV radiocommunication system should use the S or Ka frequency band. To meet operational requirements, the SoV should adopt GNSS system to obtain real-time accurate position of SoV in navigation purpose. Current GNSS systems should be used for navigation.

A5.3 Maximum Doppler frequency and Doppler acceleration

The Doppler frequency can be obtained by the following formula:

$$f_d = \frac{f}{c} \times v \times \cos\theta$$

where:

f_d = Doppler frequency

c = speed of light

f = emission frequency

v = the relative speed between the transmitter and the receiver

θ = the angle between the relative velocity vector and the vector between the receiver and the transmitter.

In addition to Doppler frequency shift, phase modulated radiocommunication utilized by SoV are affected by Doppler acceleration.

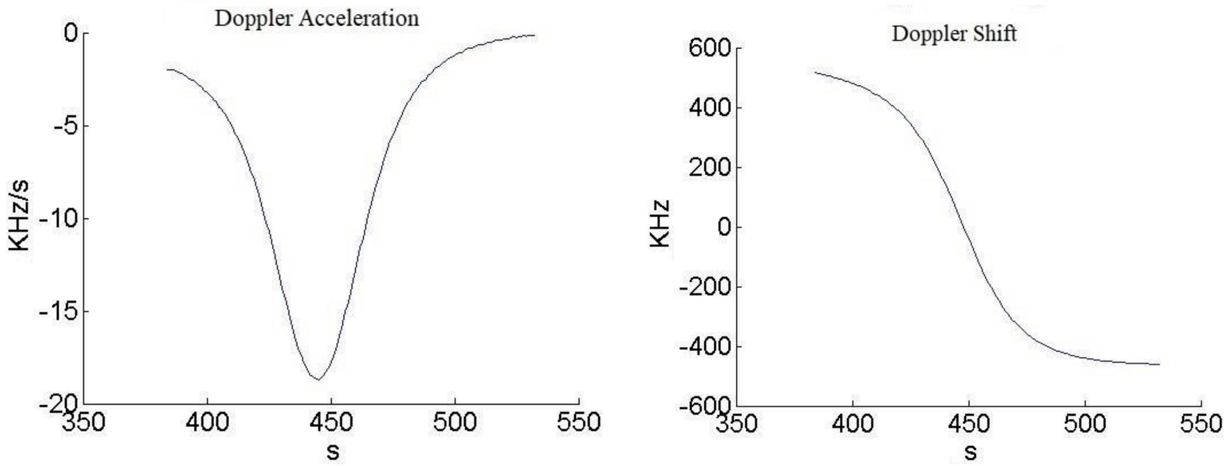
In the Figures below, the Doppler frequency shift and their Doppler acceleration by frequency band are given for the ground stations and GSO TDRS for the SoV flight trajectory shown in Fig. A5-1. Table A5-1 summarizes the results.

A5.3.1 Doppler frequencies and Doppler Acceleration for Ka-band

Doppler shift and Doppler Acceleration of Ka-band for Station01 are shown in Fig. A5-4, maximum Doppler Acceleration is −18 kHz/s, maximum Doppler shift is around 500 kHz.

FIGURE A5-4

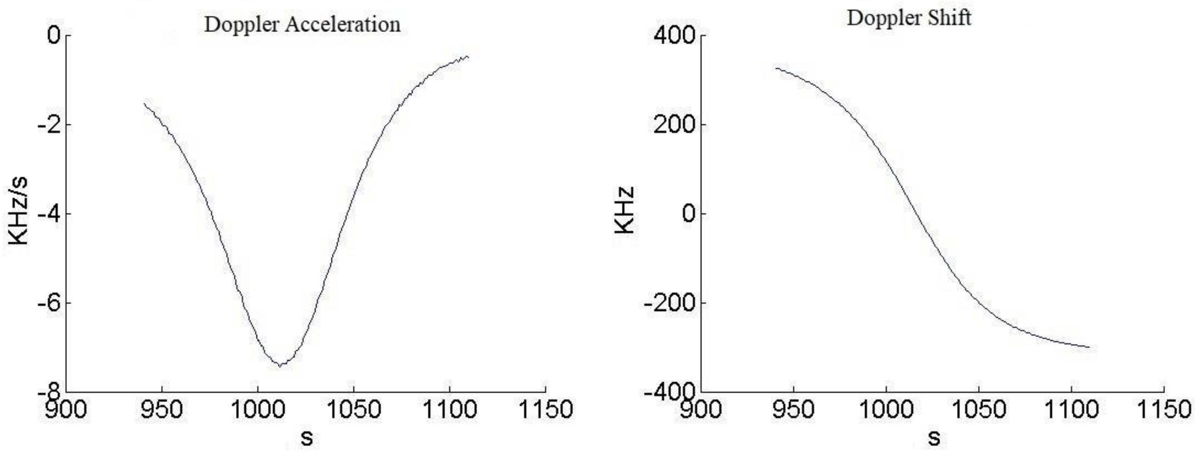
Doppler shift and Doppler acceleration of Ka-band for Station01



Doppler shift and Doppler acceleration of Ka-band for Station02 are shown in Fig. A5-5, maximum Doppler acceleration is −7.8 kHz/s, maximum Doppler shift is around 300 kHz.

FIGURE A5-5

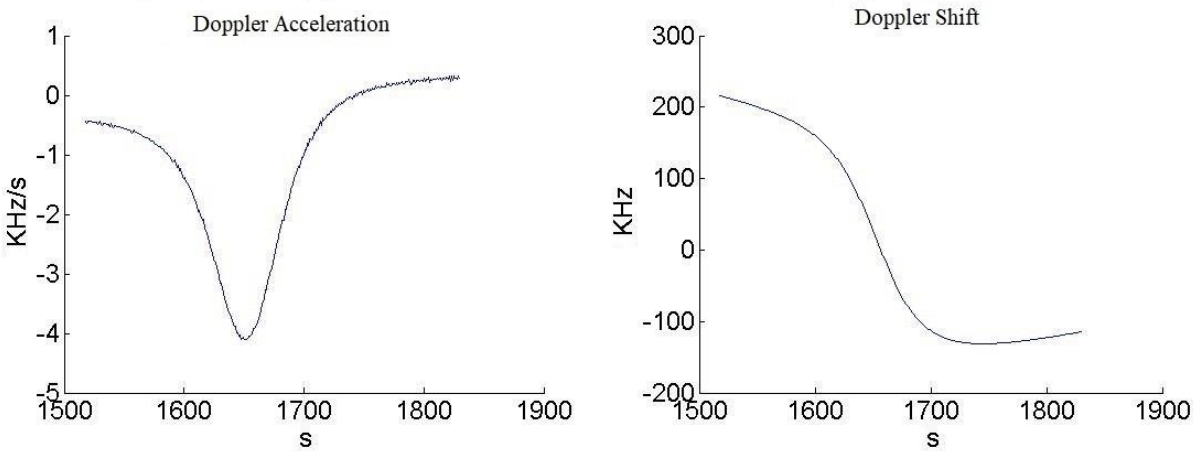
Doppler shift and Doppler acceleration of Ka-band for Station02



Doppler shift and Doppler acceleration of Ka-band for Station03 are shown in Fig. A5-6, maximum Doppler acceleration is −4 kHz/s, maximum Doppler shift is around 220 kHz.

FIGURE A5-6

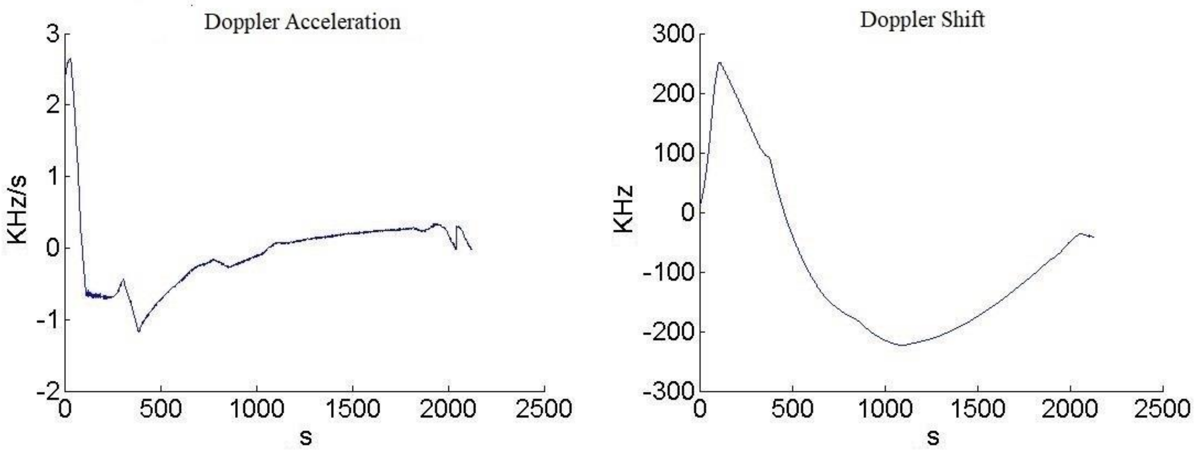
Doppler shift and Doppler acceleration of Ka-band for Station03



Doppler shift and Doppler acceleration of Ka-band for TDRS are shown in Fig. A5-7, maximum Doppler acceleration is −1.3 kHz/s, maximum Doppler shift is around 250 kHz.

FIGURE A5-7

Doppler shift and Doppler acceleration of Ka-band for GSO TDRS

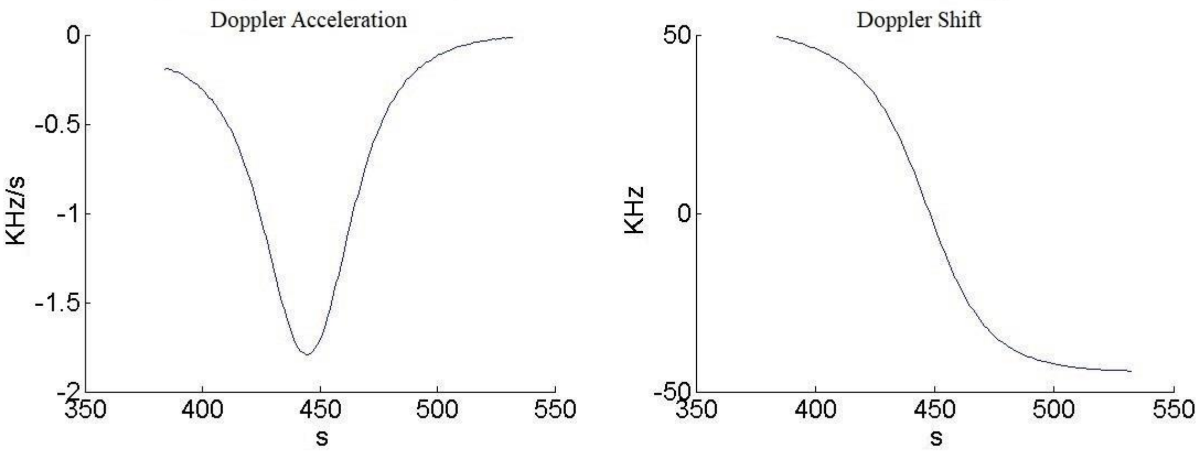


A5.3.2 Doppler shift and Doppler acceleration for S-band

Doppler shift and Doppler Acceleration of S-band for Station01 are shown in Fig. A5-8, maximum Doppler Acceleration is −1.8 kHz/s, maximum Doppler shift is around 50 kHz.

FIGURE A5-8

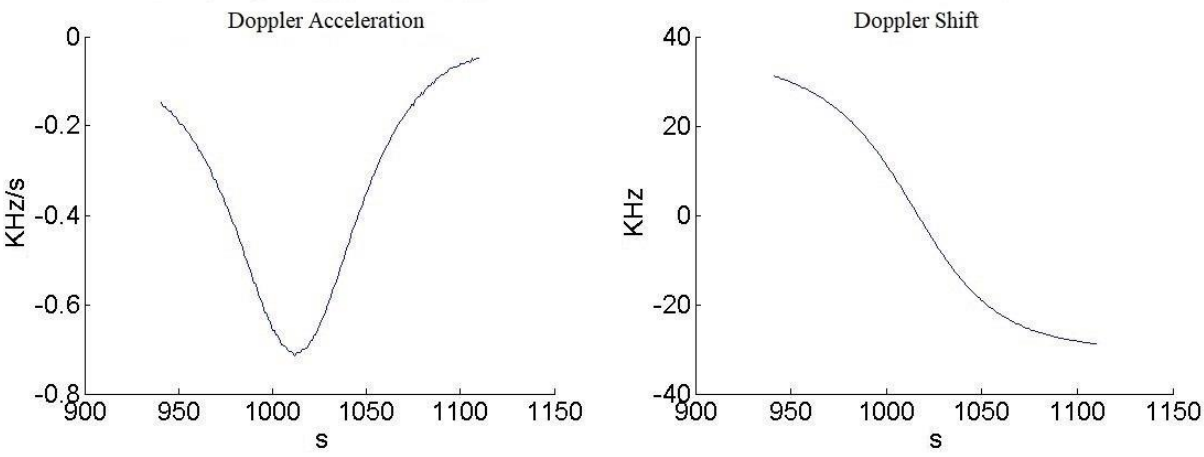
Doppler shift and Doppler acceleration of S-band for Station01



Doppler frequencies and their rates of change of S-band for Station02 are shown in Fig. A5-9, maximum Doppler acceleration is –0.7 kHz/s, maximum Doppler shift is around 30 kHz.

FIGURE A5-9

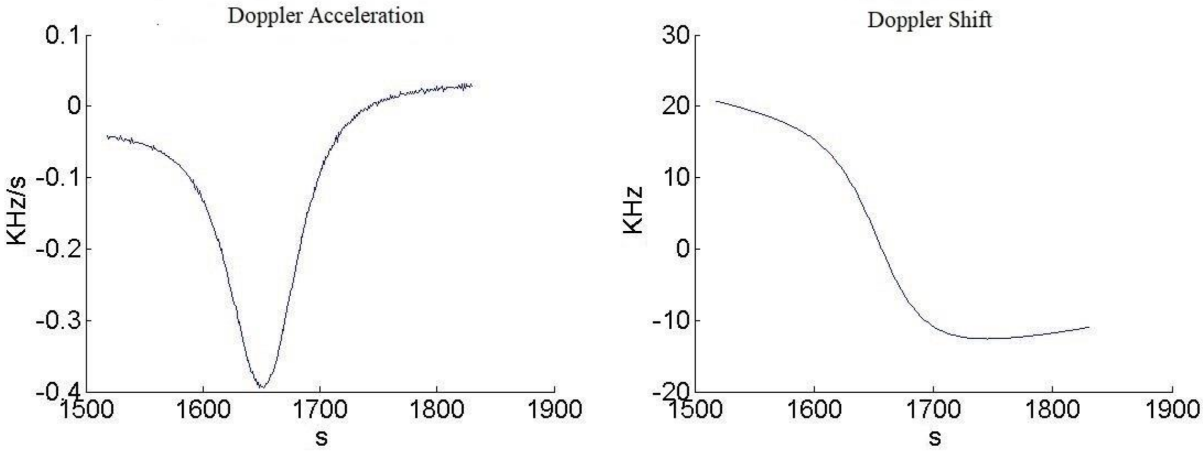
Doppler shift and Doppler acceleration of S-band for Station02



Doppler frequencies and their rates of change of S-band for Station03 are shown in Fig. A5-10, maximum Doppler Acceleration is –0.4 kHz/s, maximum Doppler shift is around 20 kHz.

FIGURE A5-10

Doppler shift and Doppler acceleration of S-band for Station03



Doppler frequencies and their rates of change of S-band for TDRS are shown in Fig. A5-11, maximum Doppler acceleration is –0.12 kHz/s, maximum Doppler shift is around 25 kHz.

FIGURE A5-11

Doppler shift and Doppler acceleration of S-band for geostationary tracking and data relay satellites

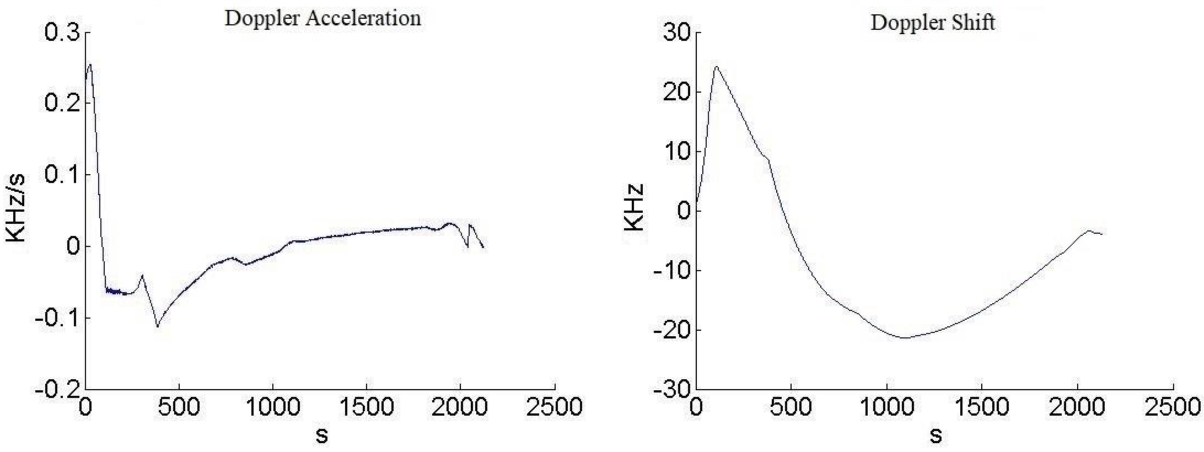


TABLE A5.1

Maximum Doppler acceleration and maximum Doppler shift for example suborbital vehicle flight

Station number or satellite	**Band**	**Maximum Doppler acceleration**	**Maximum Doppler shift**
Station01	Ka	−18 kHz/s	500 kHz
Station02	Ka	−7.8 kHz/s	300 kHz
Station03	Ka	−4 kHz/s	220 kHz
GSO TDRS	Ka	−1.3 kHz/s	250 kHz
Station01	S	−1.8 kHz/s	50 kHz
Station02	S	−0.7 kHz/s	30 kHz
Station03	S	−0.4 kHz/s	20 kHz
GSO TDRS	S	−0.12 kHz/s	25 kHz

A5.4 Requirements of overcoming re-entry communication blackout

During the high-speed flight of the SoV re-entry phase, intensive friction between the vehicle surface and the surrounding air, along with dramatic compression of the air, results in the sharp temperature rise of surrounding air which causes air ionisation and forms a plasma sheath around the vehicle. The plasma sheath introduces a high attenuation factor, often leading to full blackout of frequencies used in traditional avionics. The conventional aviation navigation systems may face challenges when serving SoV during the phases of flight with very high speed and high dynamic speed changes.

To improve safety for high speed commercial manned SoV the time duration of radiocommunication signal interruptions should be minimized or eliminated by reducing the impact of the ionisation blackout.

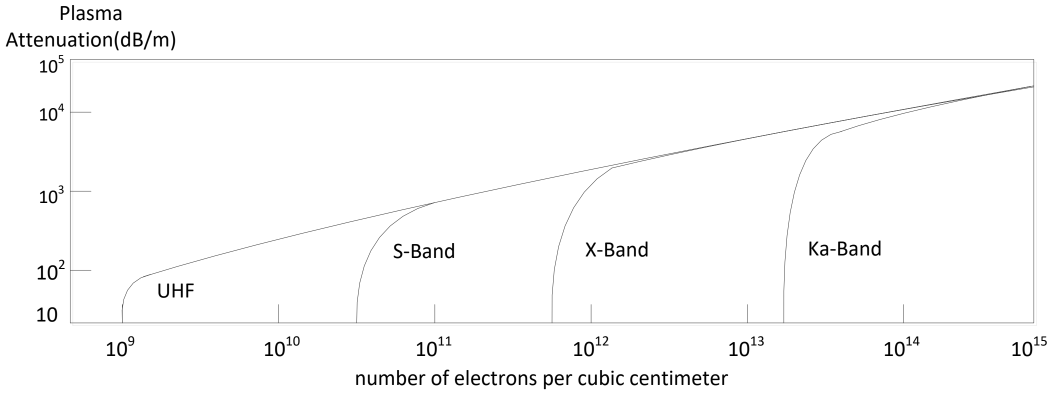
There are several ways to overcome the impact of the ionisation blackout shown in following categories:

1) Selection of appropriate frequency band – Consider using very low frequencies or VHF to minimize attenuation from ionisation blackout. (Note: very low frequencies may not be ideal due to antenna size.);
2) Increase signal power to overcome attenuation from plasma;
3) Trajectory shaping – control the shape of the plasma sheath by controlling the angle of attack and the position relative to receivers;
4) Antenna location and antenna types.

To reduce the influences of the plasma generated by the hypersonic vehicle on radiocommunication, increasing the frequency may reduce the blackout depending on the vehicle surface material, trajectory and attitude. Figure A5-12 shows the relation between the plasma attenuation and the ionisation level with different service bands

FIGURE A5-12

Plasma attenuation compared to number of electrons around the vehicle (ionisation level)



From Fig. A5-12, we can conclude that: under the same electron density, the higher the radio frequency is, the less attenuation from the plasma sheath is. In fact, according to the existing experiment and theoretical estimates, the penetration of the millimetre wave through the plasma is superior to the meter wave band and the centimetre wave band. The Ka-band communication system has advantages over S band communication systems, such as significantly higher efficiency and, in addition, the time duration of the radio communication blackout interruption can be shortened at certain altitudes. Also, due to the higher bandwidth, high-capacity data transmission in real time become possible when using Ka-band communication system.

A5.5 Spectrum criteria

Selection of different frequency bands can separately or in-joint benefit specific suborbital flight phase.

1) Existing avionics may fulfil the requirements in airspace used by conventional aircraft for suborbital flights;
2) Use GNSS for navigation, S-band for whole-period communication coverage and mitigating communication interruption, and Ka-band for overcoming radiocommunication blackout;
3) Integration of different bands and their interferences need further analysis in the following sessions;
4) Some of the existing space services may meet radiocommunication requirements, for the Doppler shift and Doppler acceleration for on-board and ground stations.

Annex 6

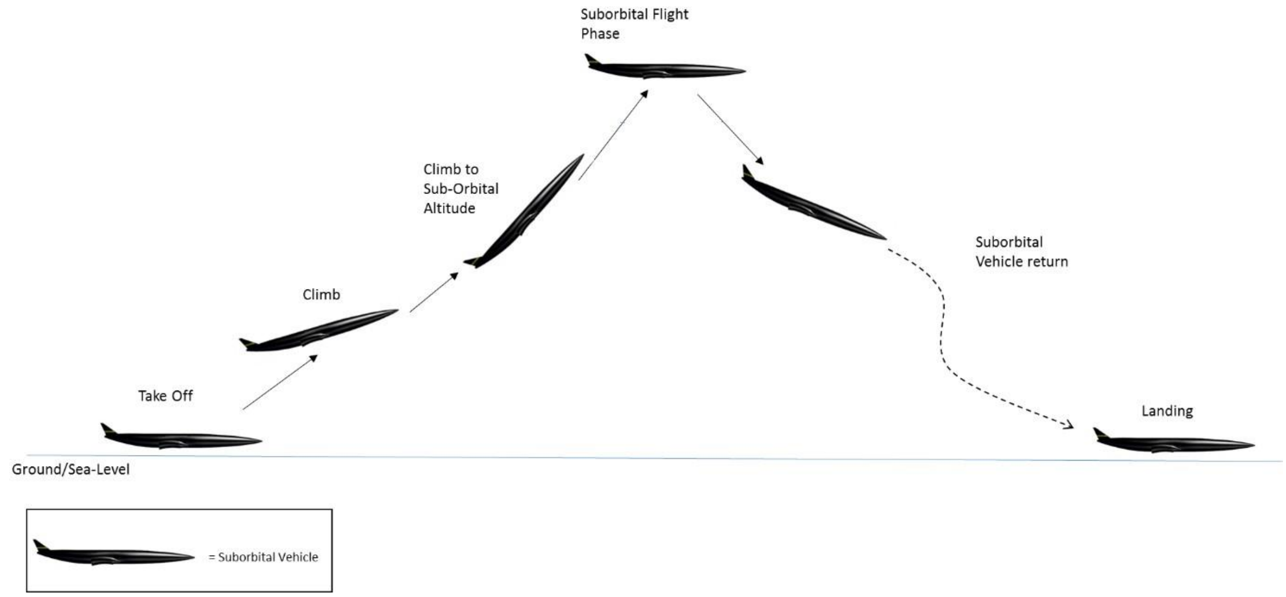
Examples of current and planned suborbital vehicle flights

A6.1 Single stage suborbital vehicle

A single-stage SoV would start directly from the ground, or sea-level location, and climb to a suborbital altitude. To perform this task the vehicle would need to bring all the fuel necessary and have a propulsion system capable of raising the vehicle to 100 km. This propulsion system may be a rocket system, or a combination of air breathing and rocket system.

FIGURE A6-1

Single stage suborbital flight (aircraft example)

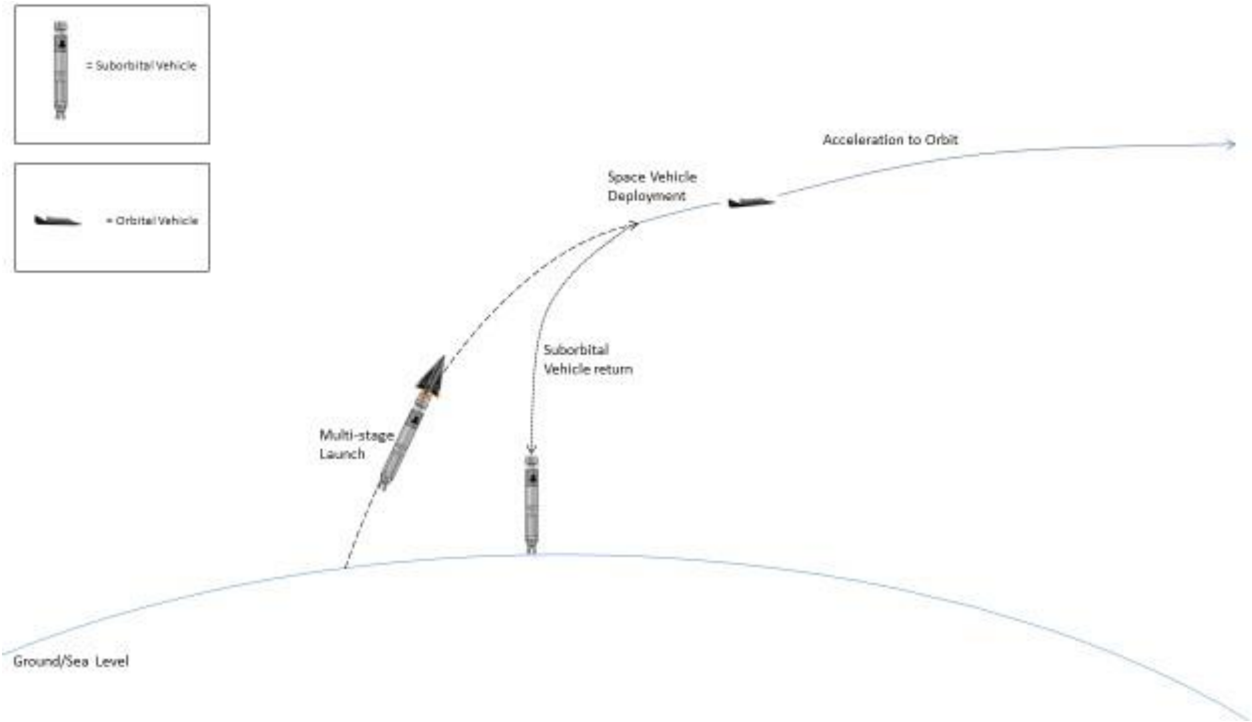


Once the SoV has reached its desired altitude, the vehicle could perform its desired mission such as deploying spacecraft, performing scientific research, space tourism, point-to-point travel, cargo transportation, or Earth observation. These flight missions may be performed as an inhabited or uninhabited vehicle. Upon completion of its mission, the vehicle would return to the atmosphere (below 100 km) and land at a designated site, such as a runway. The landing site may or not be same location where the sub-orbital vehicle performed its take-off.

An example of suborbital flight for a single-stage SoV that takes off and lands like a conventional aircraft is shown in Fig. A6-1. An example of suborbital flight for a single-stage SoV that takes off and lands like a rocket is shown in Fig. A6-2.

FIGURE A6-2

Single stage suborbital flight (rocket example)



A6.2 Multi-stage suborbital vehicle

A multi-stage SoV would be designed in such a way to optimize how fuel is used. One such approach would consist of a carrier vehicle (which is not a SoV) and a SoV. This combined vehicle takes off and gains altitude under the power of the carrier vehicle and then separates at some predetermined altitude, likely the upper boundary of the troposphere (12-17 km), from where the SoV may accelerate and climb to altitudes above 100 km. After the vehicle separation, the carrier vehicle may proceed directly to a landing site or provide an observation platform for the SoV. Once the SoV has reached its desired altitude, it could perform its desired mission such as deploying a spacecraft, performing scientific research, space tourism, point-to-point travel, cargo transportation or Earth observation, and then proceed to a landing. An example of suborbital flight for a multi-stage SoV where the carrier vehicle is an aircraft is shown in Fig. A6-3. An example of suborbital flight for a multi-stage SoV where the carrier vehicle is a rocket is shown in Fig. A6-4. An example of suborbital flight for a multi-stage SoV where both the 1st and 2nd stage reach suborbital space flight is shown in Fig. A6-5.

FIGURE A6-3

Multi-stage suborbital flight (carrier aircraft example)

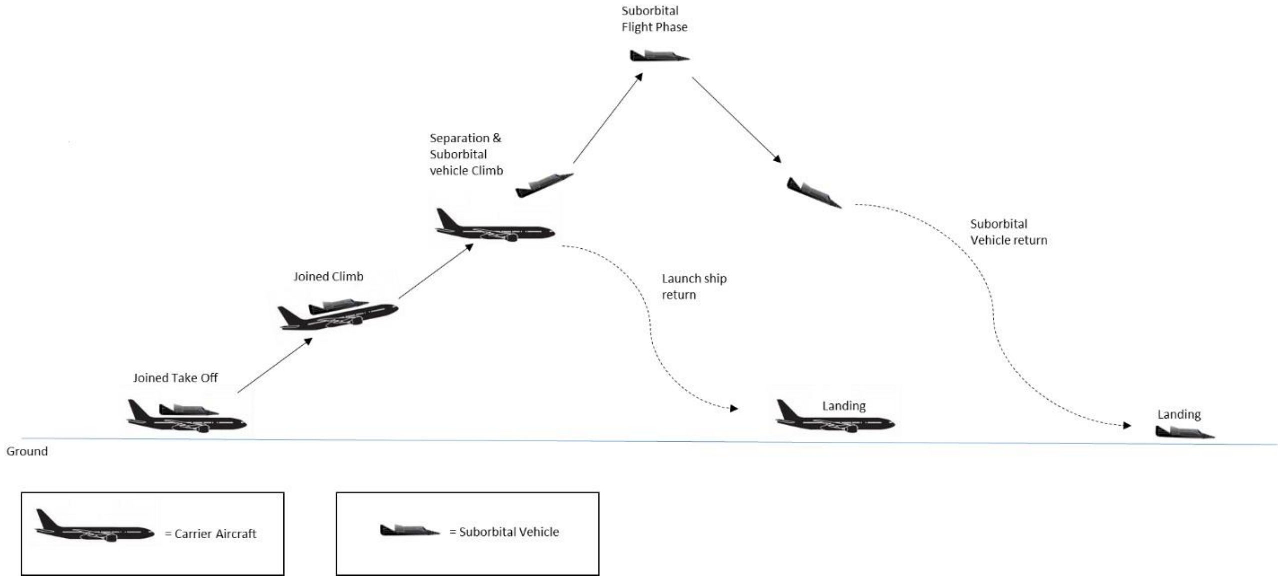
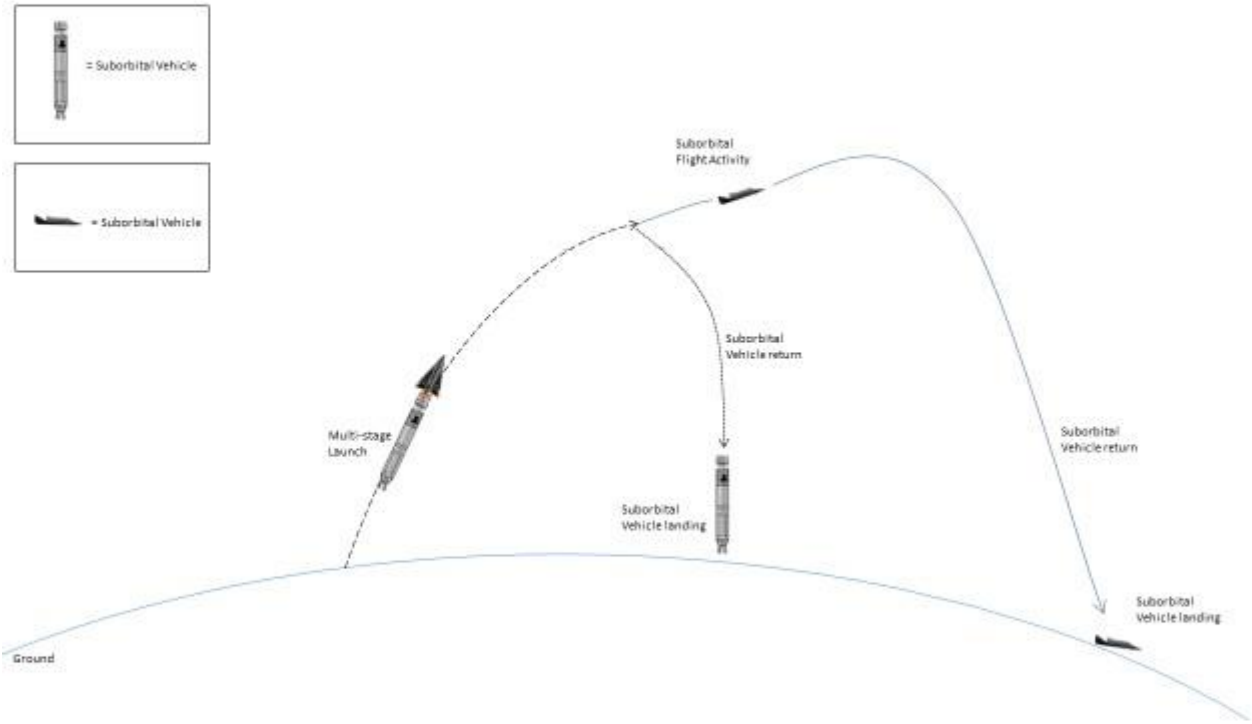


FIGURE A6-4

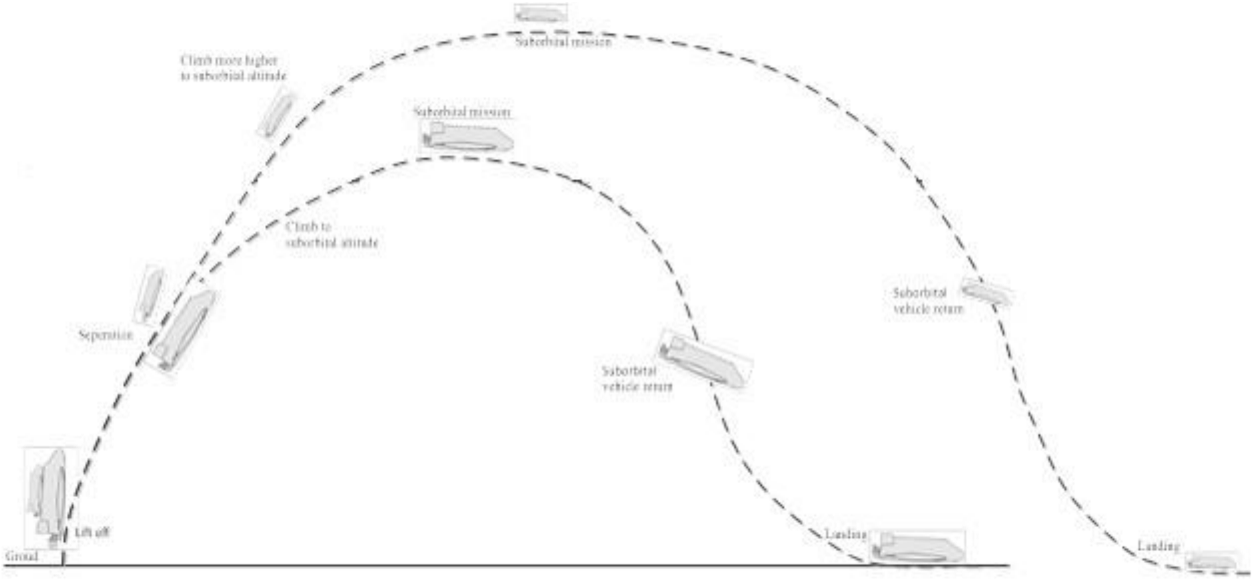
Multi-stage suborbital flight (carrier rocket example)



During one launch flight, after separation, the 1st stage performs a lower altitude suborbital task and the 2nd stage continues to climb higher to perform a higher altitude suborbital task which cannot be accomplished by 1st stage. Both SoV land on the earth after completion of the missions.

FIGURE A6-5

Multi-stage suborbital flight (double suborbital vehicles example)



SoV may be designed for short duration suborbital flights, e.g. trips that are likely to last for no more than a couple of hours in total, with perhaps a few minutes in a micro-gravity environment. However, longer suborbital flights cannot be excluded like journeys between two continents.

Such vehicles could also offer an alternative means of launching satellites. However, these satellites would need an additional propulsion system in order to reach the corresponding altitude for their insertion into the relevant orbit.