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Space operation systems

SA Series

Space applications and meteorology

International Telecommunication Union

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Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R SA.363-5*,**

Space operation systems

Frequencies, bandwidths and protection criteria

(1963-1974-1982-1986-1990-1994)

The ITU Radiocommunication Assembly,

considering

a) that the frequencies technically suitable for maintenance telemetering, tracking and telecommand of developmental and operational radionavigation, meteorological, communication, earth exploration and broadcasting satellites lie in the range from 100 MHz to 30 GHz (see Annex 1);

b) that the preferred bands of frequencies for maintenance telemetering, precision tracking and telecommand are between 1 and 8 GHz;

c) that, as an exception, bands of frequencies above about 10 GHz are technically suitable for use for maintenance telemetering, tracking and telecommand during the re-entry of satellites into the atmosphere of the Earth (see Annex 2);

d) that the integration of maintenance telemetering, tracking and telecommand links with data transmission and communication systems may have advantages which include, among others, efficient use of the spectrum particularly for the on-station operational phase of geostationary satellites;

e) that the validity of this approach has been demonstrated in some operational systems;

f) that satellite safety nonetheless requires wide-coverage antenna radiation to maintain links during specific phases of launch and orbit transfer or in cases of momentary loss of attitude, and that wide-coverage radiation is difficult to obtain at frequencies above 8 GHz;

g) that, in the case of broadcasting satellites, Appendix 30 of the Radio Regulations (RR) provides for the use of the bands 11.7 to 12.5 GHz in Region 1 and 11.7 to 12.2 GHz in Region 3 by assigning channels to the administrations in those Regions for satellite broadcasting, but no specific assignments were made for maintenance telemetering, tracking and telecommand (although RR Annex 5 to Appendix 30 specifies guard bands at the edges of both bands) and that consequently it may be difficult to use these bands also for maintenance telemetering, tracking or telecommand. In the case of Region 2, RR Appendix 30 provides that space operation systems could be used in the specified guard bands of 12 MHz at each end of the 12.2 to 12.7 GHz band and similarly, in RR Appendix 30A in the 17.3 to 17.8 GHz band;

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* This Recommendation should be brought to the attention of Radiocommunication Study Groups 4, 3, 8, 9, 10 and 11.

** Radiocommunication Study Group 7 made editorial amendments to this Recommendation in 2003 in accordance with Resolution ITU-R 44.

h) that, in most cases, the necessary bandwidths for space operations are determined by the transmission of ranging signals, and usually lie between 200 kHz and 1 MHz with classical modulation methods;

j) that the e.i.r.p. of space station transmitters is limited, so that earth receiving stations must operate at maximum sensitivity;

k) that the e.i.r.p. of earth-station transmitters can be increased within the limits defined in the RR to give an acceptable protection ratio at space station receiver inputs,

recommends

1 that bands of frequencies below 1 GHz are technically suitable for use for some types of maintenance telemetering, tracking and telecommand of developmental and operational low-orbit (for example, below 2 000 km) satellites;

2 that frequencies for maintenance telemetering, precision tracking and telecommand should be between 1 and 8 GHz;

3 that as an exception, bands of frequencies above about 10 GHz be used for maintenance telemetering, tracking and telecommand during the re-entry of satellites into the atmosphere of the Earth (see Annex 2);

4 that, for satellite systems such as those used for meteorological, radionavigation, communication, earth exploration and broadcasting purposes, and taking account of requirements for reliability and economical use of the frequency spectrum and for the safety of spacecraft in all phases of operation, frequencies within the mission bands used for data transmission or communications are preferred for use for maintenance telemetering, tracking and telecommand, where practicable. Where this is not practicable, frequencies in the bands specifically allocated to the space operation service should be used;

5 that the special needs for maintenance telemetering, tracking and telecommand be considered in the planning of frequencies for the broadcasting-satellite service and for the associated feeder links, especially for those assignments sharing one orbital location;

6 that the protection criteria for earth station receivers be as follows: for frequencies above 1 GHz, total interference power in each band 1 kHz wide must not exceed –184 dBW at the receiver input for more than 1% of the time each day; for frequencies below 1 GHz, this value is increased by 20 dB per decreasing frequency decade;

7 that the protection criteria for spacecraft receivers be as follows: the ratio of signal power to total interference power in each band 1 kHz wide must not fall below 20 dB for more than 1% of the time, each day;

8 that, as these criteria are insufficient to guarantee the safety of spacecraft in certain brief critical phases, such as launching, the administrations concerned should coordinate to guarantee the safety of spacecraft during such brief critical phases.

Annex 1

Space operation systems

Frequencies, bandwidths and protection criteria

1 Introduction

RR No. 1.23 defined the space operation service as follows:

"A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand.

These functions will normally be provided within the service in which the space station is operating."

To understand the meaning of the second sentence in the definition, it should be borne in mind that the original idea was to carry out space operation functions solely in the bands allocated to missions. Experience showed, however, that space operation could be facilitated in some cases by the specific allocation of bands to this service. In particular, this makes it possible to use a small number of stations for the space operation of satellites with missions pertaining to different services, such as the space research, meteorological-satellite, earth exploration-satellite, fixed- and mobile-satellite and broadcasting-satellite services.

Furthermore, the frequency bands technically suitable for space operation do not always coincide with the bands which are suitable to missions, and there may be different protection criteria for space operation and mission telecommunication receivers.

This Annex covers successively the functions to be carried out, the preferred frequency bands, the bandwidths, the protection criteria and various operational aspects of space operation systems.

All aspects are dealt with in such a way that the conclusions are applicable both for cases where space operation functions are performed in a frequency band related to a satellite's mission, and for cases where they are carried out in a frequency band allocated to the space operation service.

Links in space operation systems may be established either directly between spacecraft and earth stations or through data relay satellites. Only direct links are considered here. For links via data relay satellites, see Recommendations ITU-R SA.1018 and ITU-R SA.1414.

2 Space operation functions

The main functions of space operations are:

– maintenance telemetry,

– telecommand,

– tracking,

– RF sensing for attitude control.

2.1 Maintenance telemetry

To ensure the maintenance of a spacecraft, a large number of measured data, most of them with a low data rate, have to be transmitted to the Earth. They include:

– temperature measurements, either for monitoring and regulation or for correction of on-board instrument readings in the light of their temperature;

– magnetic field measurements, to provide particulars of the instantaneous attitude of the spacecraft or its rotation speed;

– measurements of moving units: separation indicators, safety stops for deployed components;

– inertial measurements (rate gyros, accelerometers), useful for satellite attitude and station keeping;

– optical measurements, to ascertain the attitude of the spacecraft in relation to the Earth, the Sun and stars;

– measurements of pressure in tanks and electrochemical batteries;

– current and voltage measurements;

– reports on the condition of a component or the reception or execution of a command.

All these measurements may be used to monitor the condition of spacecraft and their payloads which depends on the external environment and on configuration orders addressed to the spacecraft by telecommand or provided by an on-board sequencer according to a predetermined programme.

These data are useful for ensuring proper operational conditions, optimizing the spacecraft and payload mission facilities and analysing unforeseen situations. They also serve to broaden knowledge of the behaviour of materials in orbit and to improve the development of new systems.

Telemetering data from the on-board memory may be transmitted in real time or stored and subsequently transmitted.

2.2 Telecommand

Most spacecraft should be able to receive orders by telecommand. RR Nos. 1.135 and 22.1 make this mandatory in the case of the active satellites defined in RR No. 1.180.

2.2.1 In the case of short-mission spacecraft, such as launchers, most of the orders can be recorded before the flight and distributed as necessary by an on-board sequencer.

Nevertheless, space telecommand is generally used for safety purposes (e.g. stopping the propulsion of a launcher deviating from its assigned trajectory or destroying it if required).

Certain telecommand functions can also be carried out by a radar transponder operating in the radiolocation service.

2.2.2 In most other cases, telecommand is needed to modify the operation of the spacecraft and its payload:

– according to successive utilization phases during the mission,

– according to different flight phases (orbit insertion, eclipse periods, etc.), or

– as a result of abnormal events, such as operational anomalies.

The orders transmitted to the spacecraft when it is in line of sight of an earth station may be either carried out immediately or stored in a memory from which they are extracted later for execution at a time also stored in the memory.

Delayed-action telecommand is particularly important for complex spacecraft missions requiring an on-board computer. In such cases, a megabit of information may have to be transmitted in a few minutes. Satisfactory reception of telecommand signals is generally acknowledged by telemetry.

2.3 Tracking

Space tracking, i.e., the determination of the orbit, velocity or instantaneous position of an object in space by means of the propagation properties of radio waves (see RR Nos. 1.136 and 1.9) has to be carried out during every space mission to meet one or more of the following requirements.

2.3.1 Spacecraft orbit control system

Broadly speaking, this is one of the methods for controlling the orbit of a spacecraft by means of telecommand facilities and on-board propulsion systems. In practice, orbit control may be used for:

– placing in parking or transfer orbit,

– modification of orbits: e.g., for changing from a transfer orbit to the geostationary-satellite orbit,

– fine orbit correction: e.g., for geostationary satellite station-keeping and for rendezvous manoeuvres,

– returning a recoverable spacecraft to Earth.

2.3.2 Surveillance, safety, recovery

The surveillance and safety functions cover anti-collision measures for spacecraft in neighbouring orbits and prediction of the impact or landing site of re-entering launcher stages or spacecraft.

2.3.3 Orbital accuracy

Evaluation of the accuracy of launches or other orbital manoeuvres.

2.3.4 Attribution of location data to mission measurements and observations

Measurements must be related to the position where the spacecraft is situated at the moment when the measurements are taken. This is particularly important when the spacecraft is carrying out scientific measurements of its environment, such as measurements of the magnetic field, particle density, etc. It is also essential in Earth observation missions, independently of the facilities offered during these missions by identification of control points on the transmitted pictures.

2.3.5 Publication of ephemeris tables

Forecasts of visibility and the pointing angle towards the spacecraft are essential for the organization of the work of earth stations and for the pointing of such directional instruments as high-gain antennas, telescopes, etc.

2.3.6 Remarks

Tracking functions which are the main objectives of space missions, such as space geodesy and satellite radionavigation, have been deliberately omitted from the above list.

Certain space tracking functions, particularly some of those cited under § 2.3.1, 2.3.2 and 2.3.3, may be carried out under the radiolocation service, with or without the use of a spacecraft radar transponder.

3 Preferred frequency bands

From the technical point of view, the space operation functions described in the preceding paragraph may be carried out in the frequency range between approximately 100 MHz and 30 GHz.

In the special case of communications effected during the re-entry of a spacecraft into the Earth's atmosphere, frequencies of 10 GHz or higher must be chosen (see Annex 2). In other cases, the technical choice of frequencies mainly depends on the factors described below.

3.1 Lower limits

The lower limit of frequencies for space operations is bound up with the effect of ionospheric propagation on the accuracy of tracking measurements.

3.1.1 Ionospheric effects on tracking accuracy

Recommendation ITU-R P.531 provides the ionospheric propagation data and prediction methods used for the design of satellite systems.

A typical error in ranging carried out by group delay measurement is 400 m for a vertical path at 100 MHz. For very low elevation angles, the value should be multiplied by about three. Real values, however, can vary considerably and may be up to ten times smaller or greater. In practice, it is impossible to correct these errors by using models, owing to the great time and space variability of the ionosphere. To reduce ionospheric errors, the frequencies used must be sufficiently high, since the error follows a $1/f^2$ law. (A frequency pair may also be used.) At 1 GHz, for example, the typical error for a vertical path is 4 m and for very low elevations, 12 m.

The remarks made with regard to group delay distance measurements also apply to phase delay measurements, except that the error has the opposite sign (apparent shortening instead of lengthening).

Error in the pointing direction of an autotrack antenna at 30° elevation has a typical value of 0.5 mrad at 100 MHz and exceeds 2.5 mrad in less than 10% of cases. These values also follow a $1/f^2$ law and should be divided by 100 for a frequency of 1 GHz.

Range rate and interferometric measurements are affected by the ionosphere in a similar way as range and angle measurements. They are further affected by the microstructure of the ionosphere, i.e., the differential effect of the ionosphere on the two paths measured for difference. Nevertheless, these subsidiary effects are generally less serious than the main ones, and like the latter they decrease with increasing frequency.

3.1.2 Necessary tracking accuracy – effect on choice of frequencies

The required accuracy of tracking measurements depends on a satellite's mission, and also on the number of earth stations involved in tracking and on their geographical location on the Earth's surface and in relation to the satellite orbit.

For many application missions, the satellites have to be maintained in a specific orbit. The two most usual cases are station-keeping with a geostationary satellite and keeping an Earth exploration satellite in heliosynchronous orbit. In both these cases, the required accuracy is about 50 m, on the assumption that a small number of stations is appropriately distributed.

Since the overall accuracy of the measuring system depends not only on the ionosphere but also on other factors, particularly on the quality of the measuring instrument, the share due to the ionosphere should be less than 50 m. In the light of the foregoing, this condition begins to be fulfilled from the moment that the frequency exceeds 1 GHz.

In conclusion, it may be assumed that from the point of view of tracking accuracy most application missions require frequencies above 1 GHz. This conclusion also applies to certain scientific missions, although some scientific missions (for astronomy, for example) and some types of application missions can be effected with lower accuracy and therefore at frequencies below 1 GHz.

3.2 Upper limit

Although the frequency range to be used for space operations is approximately 100 MHz to 30 GHz, the upper part of this range is generally less favourable when a link has to be established or maintained in all operating phases of a space system. A frequent requirement, in fact, is the possibility of establishing at any moment, or permanently maintaining, telemetry or telecommand links, i.e., independent of the spacecraft attitude. For this reason, a great number of satellites rely on quasi-omnidirectional antenna coverage for space operations.

For large satellites with complex structures such antennas are frequently difficult to implement at frequencies above 8 GHz. At higher frequencies, spacecraft antenna coverage will not be any more quasi-omnidirectional, but be restricted to certain aspect angles. This can result in a loss of RF contact with the satellite for unfavourable aspect angles.

Furthermore, at frequencies above 15 GHz additional propagation conditions in the atmosphere may lead to a deterioration of the link, unless either the transmitted power or the G/T of the receiving station is considerably increased.

In these circumstances, the antenna gain to be taken into account in drawing up the link budget is not that of the main lobe minus 3 dB, as is usual for mission telecommunications, but is the gain guaranteed in the troughs within the minimum required coverage. The gain in the trough depends not only on antenna design, but also on antenna layout and the dimensions and shape of the spacecraft structure and its appendages such as booms, solar panels, other antennas, etc.

The masking effect produced by the body of the spacecraft may be reduced by placing the antenna at the end of a suitably long boom. There could also be an automatic system aboard the spacecraft to guarantee the link performance with the earth station in the event of loss of nominal attitude. This link may be intermittent.

The range of 100 MHz to 30 GHz should be divided into three sub-ranges:

– below 1 GHz:

  the body of the satellite affects the radiation pattern, which may be an advantage for small satellites (less than 1 m) and a disadvantage for larger ones;

– 1 to 8 GHz:

  the radiation is mainly defined by the characteristics and arrangement of the antennas;

– 8 to 30 GHz:

  obtaining the required radiation entails stricter constraints on the design and manufacture of the spacecraft antennas.

It appears that the highest frequency used so far for links which are independent of the attitude of the spacecraft is 6 425 MHz, but current projects provide for the use of frequencies as high as 14 GHz.

3.3 Other factors to be taken into account in choosing frequencies

To facilitate decoupling of Earth-to-space and space-to-Earth links while using the same antenna in both directions, the ratio between the frequencies of the two links should be between 1.06 and 1.1.

To optimize spectrum utilization, it would be desirable for all space systems operating in these bands to adopt the same ratio. However this approach may not always be possible, in particular at earth station sites located within areas covered by dense terrestrial networks, operating in the same frequency band. In the bands 2 025-2 120 MHz and 2 200-2 300 MHz, various space systems already in operation use coherent transponders with a frequency ratio of 240/221 between the downlink/uplink permitting range rate measurements.

3.4 Summary of preferred frequency bands

In summary, the preferred frequencies for space operations lie approximately between 1 and 8 GHz.

Lower frequencies may be used, particularly for small spacecraft carrying out missions which do not call for high-precision tracking.

Higher frequencies may be preferred for space operation functions of spacecraft using these frequencies as well for mission links with the Earth.

4 Necessary bandwidth

From the point of view of bandwidth requirements, a distinction should be made between launchers and other spacecraft.

In the case of launchers, the bandwidth of the space-to-Earth link is related to the transmission of many rapidly changing parameters, mainly vibrations and pressures.

In the other cases, the bandwidth of the space-to-Earth link is generally determined, not by telemetry, but by ranging signals.

With regard to the Earth-to-space link, the necessary bandwidth is also generally determined by the transmission of ranging signals.

In conclusion, the necessary bandwidths are generally determined by the transmission of ranging signals and are of the order of 200 kHz to 1 MHz for classical modulation methods. New modulation techniques such as spread spectrum will require bandwidths in excess of 1 MHz while allowing a multiple re-use of the same band. Lower values may suffice if tracking is effected by interferometry or by range rate measurement (Doppler effect measured on the carrier).

5 Protection criteria

5.1 Protection level of earth station receivers

Attempts are generally made to reduce the necessary power of on-board transmitters to a minimum, and earth station receivers therefore have to operate at maximum sensitivity.

Above 1 GHz, it is considered that the total noise temperature of earth stations is 100 K or more which at the receiver input is equivalent to a noise power spectral density of $kT \geq -208.6$ dB(W/Hz).

It is considered that in most cases additional protection of about 5 dB is required against all types of interference.

The total interference power spectral density must therefore not exceed –214 dB(W/Hz) at the receiver input.

Below 1 GHz, owing to the increase in galactic noise temperature, the permissible interference level may be raised by 20 dB per decreasing frequency decade.

5.2 Protection ratio of space station receivers

The power of earth station transmitters can generally be increased within the limits imposed by the RR and on-board receivers therefore do not always operate at maximum sensitivity. In particular, for communication with low-altitude satellites operating close to sources of interference from terrestrial services, the transmitted power of earth stations can be kept as high as for geostationary satellites for example, in order to keep an adequate signal-to-interference ratio.

The protection of space station receivers is therefore more conveniently expressed by protection ratios than by protection levels.

A signal-to-total interference protection ratio of 20 dB is sufficient in most cases.

5.3 Reference bandwidth

The reference bandwidth in which the protection level or ratio must be specified depends on the characteristics of the receivers used and their susceptibility to continuous wave, amplitude modulated or low-index modulation phase-modulated interferences. Phase-locked receivers are often used; in such cases the reaction of the receiver to a narrow-band interfering source is characterized by the equivalent noise bandwidth of the loop. This bandwidth is normally fixed at a value between a few hundred hertz and a few kilohertz. A value of 1 kHz may therefore be adopted for the reference bandwidth.

5.4 Reference percentage of time

Generally the percentage of time during which space operation links can tolerate an interference level above the protection level may be fixed at 1% each day. This value is based on the assumption that the spacecraft is equipped with memory and automatic devices to ensure its safety during interruptions of telecommunications. This condition was not always fulfilled in the past, but it is considered reasonable to require it to be met by future systems.

However interference lasting for as long as 15 consecutive minutes is intolerable during certain foreseeable critical stages, such as launch phases, critical spacecraft manœuvres, or for such short-lived spacecraft as rocket probes. It would be unreasonable to lay down protection criteria on the basis of such exceptional situations, and it would be preferable to invite concerned administrations to carry out special analyses of the interference likely to be caused and to take countermeasures which should be temporary and limited to specific regions.

5.5 Conclusions on protection criteria

For earth stations carrying out space operation functions, above 1 GHz, the total interference power at the receiver input in any 1 kHz band should not exceed –184 dBW for more than 1% of the time each day; below 1 GHz, this value may be increased by 20 dB per decreasing frequency decade.

For space stations carrying out space operation functions, the ratio of signal power to total interference power in any 1 kHz band should not fall below 20 dB for a period exceeding 1% of the time each day.

6 Operational aspects

A comparison is given below of the advantages and disadvantages of the use for space operation functions of mission frequency bands and frequency bands allocated to the space operation service or a combination of the two.

6.1 Use of mission telecommunication bands for space operation

6.1.1 Advantages

Since most spacecraft are equipped with transmitters and receivers for telecommunications directly concerned with their mission, it is generally preferable to use the same equipments for maintenance telemetry, telecommand and tracking, in order to reduce the cost of on-board and earth station equipment and to economize the spectrum.

6.1.2 Disadvantages

Experience shows that this mode of operation is not always the best:

– when frequencies above 7 GHz are used for mission telecommunications, it is often difficult to ensure on board the spacecraft the necessary radiation pattern to guarantee maintenance of links during launching and during nominal attitude loss phases;

– in certain frequency bands allocated to mission telecommunications, the allotment plans do not provide specifically for the transmission of space operation data;

– economy of on-board equipment is less than it appears at first sight in those cases where it becomes necessary to install a wide-coverage antenna system for space operation functions in addition to the directional radiation antennas usually used for mission telecommunications;

– economy of earth station equipment is also not necessarily guaranteed, since space operation functions may necessitate a geographical location of stations different from that required for mission functions.

6.2 Use of specific space operation service bands

6.2.1 Advantages

In view of all the expenditure on board and on the ground, it may be cheaper to have a single network of earth stations for space operation. These would operate with satellites carrying out missions for several services to which different frequency bands are allocated. The common network would use frequencies allocated specifically to the space operation service.

6.2.2 Disadvantages

The advantage of a multi-purpose earth station network using frequencies allocated exclusively to the space operation service and working with several spacecraft is limited if some of the spacecraft require the permanent operation of telemetry links, which would make it necessary to increase the number of earth stations. This would reduce, particularly for geostationary satellites, the efficient use of frequencies and increase the interference potential.

6.3 Combined use of mission and specific frequency bands

In conclusion, the best solution, especially for mission telecommunications using frequencies above 8 GHz, may be to equip spacecraft with two maintenance telemetry, telecommand and tracking systems, one operating in the band allocated to the mission and the other in the frequency band which is most suitable for space operations, i.e., the band 1-8 GHz. The first system would be used preferably in the routine phases and could be brought into operation by mission telecommunication earth stations or by a specialized earth station; the second system would be used during the launch phase and during other critical phases, without unduly overloading the multi-purpose earth station network. The additional cost of the on-board equipment is less than might appear at first sight, because the telemetry encoder and the telecommand decoder would not have to be duplicated and because the on-board antennas would have to be duplicated in any case to ensure the necessary coverage during critical phases. The additional cost of ground equipment would be shared between the user systems. To offset these additional investments, this solution would ensure the greatest operational reliability and flexibility at all phases of the mission without entailing any appreciable increase in operational costs.

Annex 2

Effects of artificial plasmas on communications with spacecraft

1 Introduction

Some communication problems arise from the presence of a plasma, e.g., ionized air, in the vicinity of a spacecraft and its antenna. Natural plasmas are present in the ionospheres of Earth and other planets, but also as "solar wind" in interplanetary space, especially in the neighbourhood of the Sun. Artificial plasmas are produced mainly by two mechanisms:

– as "ionized gases" generated by spacecraft propulsion and control systems, and

– as "plasma sheath" forming around a spacecraft entering a planetary atmosphere.

Two main effects of plasmas must be considered, namely:

– that on antenna performance, and

– that on propagation of radio waves.

This Annex gives a summary of the effects of artificial plasmas on communications with spacecraft.

2 Summary of atmospheric entry plasma effects

Atmospheric entry plasma effects on communications will vary greatly with the mission, which determines the vehicle trajectory and configuration. Selection of signal frequency, antenna location, and antenna type can be used to circumvent or minimize the re-entry signal loss in many cases. Criteria which influence this selection include the plasma thickness, collision frequency, ablation material, and the nature of the non-equilibrium phenomena (i.e., producing or recombining type plasma). Also practical considerations such as power requirements, signal modulation techniques, tracking station capabilities, and relative location with respect to the spacecraft (look angle) enter into the selection.

Some experimental results indicate that the critical frequency of the plasma sheath is often as high as 1 to 10 GHz and may sometimes be even higher. It is concluded that frequencies of 10 GHz or higher are technically required for certain re-entry communications, especially for re-entry from lunar or planetary missions.

At these frequencies, absorption in the planetary atmospheres can be very important. For the atmosphere of the Earth, Recommendation ITU-R P.676 refers to relevant information. It also shows that there are several “windows” above 60 GHz where the absorption in atmospheric gases may be acceptably low. The data, however, indicate that attenuation in tropospheric precipitation could be prohibitively high. Frequencies near 90 GHz and perhaps those near 140 GHz might be preferable in this respect.

Other experimental programmes have demonstrated an increased understanding of the re-entry plasma sheath. Data from in-flight measurements at orbital re-entry velocities using diagnostic antennas and rakes of immersed electrostatic probes are in excellent agreement with theory, except at the extremities of the plasma attenuation period. The electrostatic probe measurements agree not only in peak plasma density, but also in the plasma profile.

Moreover, the effects of the plasma sheath have been reduced by modifying the plasma itself; for example, by aerodynamic shaping (sharp nose or spike configurations) to reduce the plasma thickness; by the injection of liquid materials into the flow field that have restored radio-frequency signals otherwise blacked out by the plasma during the re-entry attenuation period; and by the choice of ablation materials which can significantly affect plasma density. Also, by sufficiently applying a strong magnetic field the configuration could be influenced and/or a propagation window could be produced, by the so-called “whistler mode”. Possibly, combinations of these techniques may be used to reduce the plasma sheath effects.

3 Summary of rocket exhaust plasma effects

Exhaust plasma is always produced in the flames of rocket motors, but may also appear in other propulsion systems, for example, electric propulsion. In its origin and as a result of different boundary conditions such a plasma is different from a typical re-entry plasma.

To describe an exhaust plasma, the factors associated with the flame must be known, such as fuel and oxidant composition, mixture ratio, alkali metal impurities, nozzle characteristics, thermo-chemical kinetics, dynamics of the expanding gases, etc. With these factors and knowledge of ambient atmospheric conditions the exhaust plume structure may be deduced. Changes in gas flow due to induced turbulence are now understood and can be included in calculations of exhaust structure. Problems introduced by the use of multiple jets are outstanding and still require further study.

Practical and theoretical investigations have been conducted and have led to methods for predicting the effects of exhaust gases. Because the plasma configuration is not one of a sheath surrounding the vehicle it presents problems different from those of re-entry. Plasma densities differ and the antenna is unlikely to be immersed in the plasma; consequently alternative propagation paths may be found (other than through the most highly ionized regions). Plasma effects include absorption, refraction, diffraction, amplitude and phase modulation. Total signal loss can be a combination of these effects. Absorption depends upon electron concentration and collision frequency, the approximate distribution of which can be deduced from a knowledge of the motor design. Significant diffraction may occur in an exhaust where the absorption is high. Spurious modulation will be encountered due to forward scattering into the antenna from the turbulent jet stream. Doppler displaced frequencies given by varying eddy velocities within the exhaust, produce plume related spectra. Comparison between experimentally derived and computed spectra is good. Radar echoing (back scatter) has been treated in a similar manner. The propagation path relative to the exhaust is another important factor; refraction effects on the ray path may not always be negligible.

As an example, for a large chemical rocket firing into a vacuum, the exhaust in the immediate vicinity of the nozzle exit is a high-pressure plasma having an electron collision frequency of about 10^{11}/s and an electron density of 10^{16} to 10^{17} per m^3. It is therefore a region of high damping with marked resonances (critical frequencies). Subsequent expansion of the gases results in a transition from this collision dominated region to effectively collision free conditions. Radio blackout due to critical frequency effects alone, is possible only in those regions of the plume where the collision frequency is less than 10^8/s. Due to the expansion of the efflux, this order of collision frequency is necessarily associated with a low electron density ($10^{13}/m^3$); this means that there is a high probability that radio frequencies down to 100 MHz, or even below, will penetrate the entire flame. Nevertheless, the overall absorption measured can be large (10 to 30 dB), due entirely to the long path lengths through the flame, encountered in certain directions. Experimental confirmation for predictions has been sought by measurements on the ground and during actual rocket launches.

Other work has been directed towards improvement of the prediction techniques, particularly the fluid dynamics, the representation of turbulent fluctuations and in the treatment of chemical processes within the exhaust. Fluid dynamic calculations have been improved by the inclusion of shock structure and a better description of the effects of forward flight on the plume, including treatment of base recirculation. Methods are now available for determination of those turbulent quantities, i.e., turbulent length scale and turbulent intensity, needed to describe electromagnetic scattering by exhaust gases. The effect of finite rate chemical reactions are included during the calculation of plume structure, this being particularly important for the calculation of electron density since this is strongly influenced by chemical reaction at low and intermediate altitudes. The major interest has been in the field of tactical rockets; nevertheless, these studies are complementary to the problems of space vehicle exhausts and can be directly related to situations encountered in space flight.