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Intermodulation Interference Modelling for Low Earth Orbiting Satellite Ground Stations

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1. Introduction

Microsatellites in Low Earth Orbits (LEO) have been in use for the past two decades. Low Earth Orbit satellites are used for public communication and also for scientific purposes. Low Earth Orbits vary with the type of satellites and their primarily purposes. Low Earth Orbit scientific satellites have very wide application, including Earth's surveillance and astronomy applications. These satellites provide opportunity for investigations for which existing techniques are either difficult or impossible to be applied. Thus, it may be expected that such missions will be further developed in the near future especially in fields where similar experiments by purely Earth-based means are impracticable (Cakaj & Malaric, 2007). Ground stations have to be established in order to communicate with such satellites, and the quality of communication depends on the performance of the satellite ground station, in addition to that of the satellite. Usually, these scientific satellites communicate with ground stations at S-band. Before the implementation of the ground station the analyses related to environmental factors have to be considered, especially in urban areas (Keim et al., 2004). Among these factors which could disturb ground station's performance is the intermodulation interference because of permanent presence of ground station uplink signal. At the ground stations located in urban areas with high density of mobile radio systems it is not easy to eliminate intermodulation interference, since these signals are unpredictable. Intermodulation products generated by radiofrequency (RF) signals present in the front end of the satellite ground station and uplink satellite signal are potential to disturb, especially in urban areas. Each case specifically should be studied with on site respective experimental investigations. These intermodulation products are caused because of eventual non-linearity at the low noise amplifier (LNA) used at the downlink of the ground station. The most influent are the third order of intermodulation products. Thus, only third order of intermodulation products is further considered.

Modelling process approach is an attempt to generalize the case and to make conclusions in advance before final decision about: location, operation frequency up to device selection for the ground satellite station implementation. Thus, interference of intermodulation products caused by uplink signal and any other radiofrequency signal presents in the front end of the ground station's receiving system is mathematically analyzed and then further modelled.

Based on the modelling concept, the intermodulation interference calculator is introduced as a main application point of this chapter.

In order to better understand the problem of intermodulation interference at satellite ground stations, the general aspects of satellite communications, orbits, artificial satellites and satellite ground stations are briefly explained.

2. General aspects of satellite communications

The basic resources available for satellite communications are *orbits* and *radio frequency spectrum* (RF). The typical satellite communication system comprises of a *ground segment*, *space segment* and *control segment*. The link which transmits radio waves from the ground station to the satellite is called *uplink*. The satellite in turn transmits to the ground station by the *downlink*. The ground segment consists of all the ground stations. The function of the *ground segment* (one or more ground stations) is to receive or transmit the information to the satellite in the most reliable manner while retaining the desired signal quality. The *space segment* consists of one or more artificial satellites. In case of more satellites they are organized in a network called *constellation*. The *control segment* consists of all ground facilities for control, monitoring and tracking the satellite.

There are two typical concepts of ground stations: single antenna system with the duplexer and double antenna system. At the single antenna concept, the separation of the transmission and reception is achieved by means of duplexer (Maral & Bousquet, 2002). Since, the discussion in this chapter is related to the satellite ground station performance, the typical ground satellite station architecture is presented in Fig. 1.
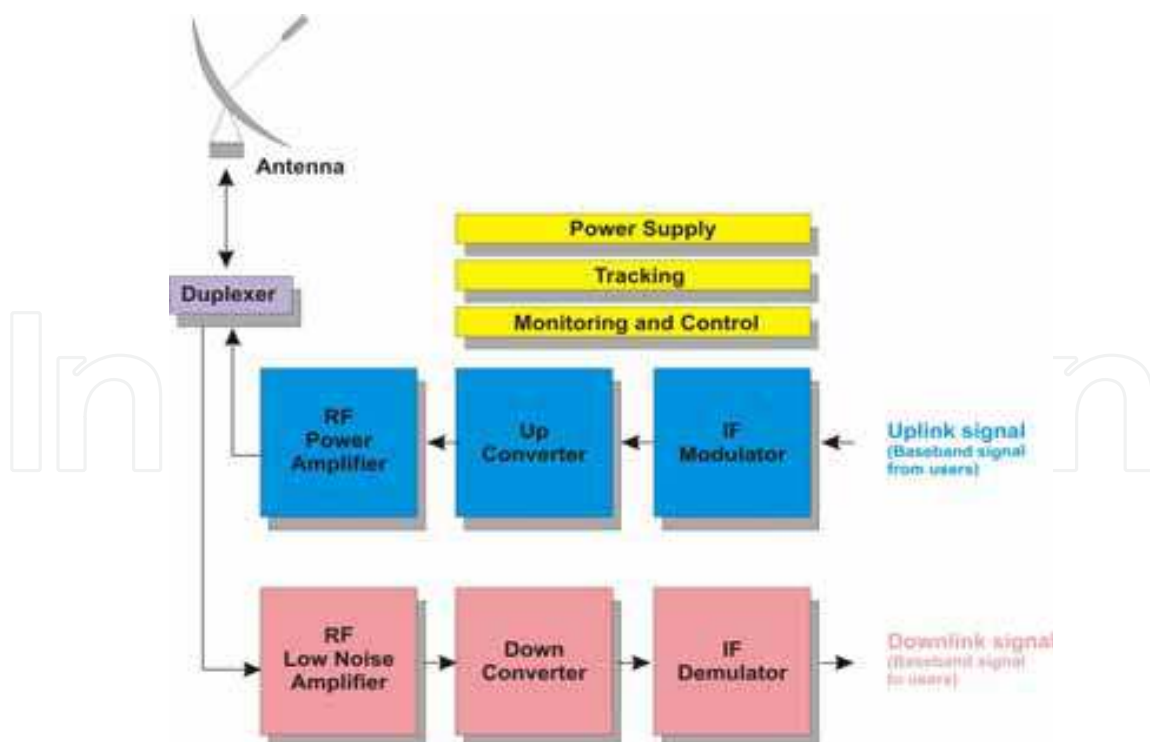

Fig. 1. The typical satellite ground station architecture

The *coverage area* (footprint) is defined as a region on the Earth from where the satellite is seen under a minimum predefined elevation angle (Cakaj et al., 2007). The communication between the satellite and a ground station is established only when the satellite is visible from the ground station. Before the implementation of ground station, analyses related to environmental factors have to be considered, especially in urban areas. Rain effects, the impact of intermodulation interference, and contact time duration under low elevation angles, are some of the aspects which should be considered due the final decision on the design of the ground station (Cakaj & Malaric, 2007).

The functionality of ground station can be disturbed because of the interference, since interference may be considered as a form of noise. Effects of interference must be assessed in terms of what is tolerable disturbing level to the end user receiver. Interference effect to the end user receiver will depend on the amount of frequency overlap between the interfering spectrum and the wanted channel passband (Richharia, 1999).

Aspects of intermodulation interference impact on performance of the low Earth orbiting satellite ground stations are further analyzed within this chapter and then closed with modeling concept of appropriate interference.

3. Orbits

The path of the satellite's motion is an *orbit*. The orbit lies in the *orbital plane*. In order to describe the satellite's movement within its orbit in space, a few parameters are required to be defined. These are known as *space orbital parameters* schematically presented in Fig. 2 and defined under below items a), b), c) and d) (Maral & Bousquet, 2002; Richharia, 1999; Roddy, 2006).
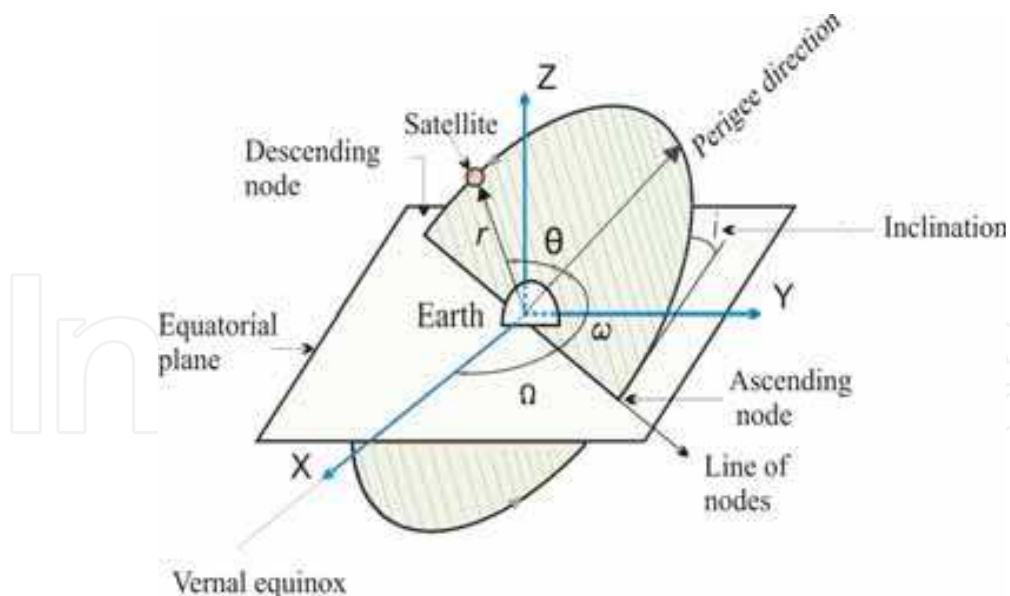

Fig. 2. Space orbital parameters

a) *The position of the orbital plane in space.*
This is specified by means of two parameters - the *inclination i* and the *right ascension of the ascending node Ω.* Inclination *i* represents the angle of the orbital plane with respect to the Earth's equator. The right ascension of the ascending node *Ω* defines the location of the ascending and descending orbital crossing nodes (these two nodes make a *line of nodes*) with respect to a fixed direction in space. The fixed direction is Vernal equinox. Vernal equinox is direction of line joining the Earth's and the Sun's center on the first day of the spring (Maral & Bousquet, 2002).
b) *Location of the orbit in orbital plane.*
Normally an infinite number of orbits can be laid within an orbital plane. So, the orientation of the orbit in its plane is defined by the *argument of perigee ω.* This is the angle, taken positively from 0° to 360° in the direction of the satellite's motion, between the direction of the ascending node and the direction of perigee (Maral & Bousquet, 2002; Richharia, 1999; Roddy, 2006).
 c) *Position of the satellite in the orbit.*
The position of the satellite in orbit is determined by the angle *θ* called the *true anomaly,* which is the angle measured positively in the direction of satellite's movement from 0° to 360°, between the direction of perigee and the position of the satellite (Maral & Bousquet, 2002; Richharia, 1999; Roddy, 2006).
d) *The shape of orbit.*
The shape of orbit is presented by the *semi-major axis a* which defines the size of orbit and the *eccentricity e* which defines the ellipticity of an orbit. The orbit is a trajectory within an orbital plane with a maximum extension from the Earth center at the *apogee* (r_a) and the minimum at the *perigee* (r_p) as presented in Fig. 3 (Richharia, 1999).
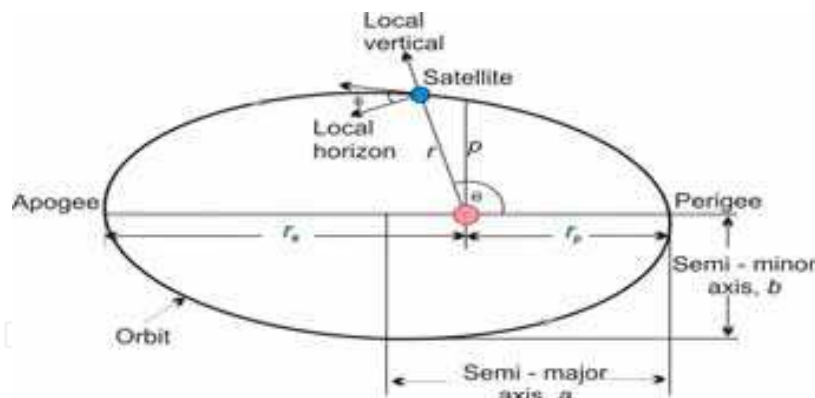

Fig. 3. Major parameters of an elliptical orbit

The eccentricity is defined as the ratio of difference to sum of apogee (r_a) and perigee (r_p) raddi as in Eqn. 1.

$$e = \frac{r_a - r_p}{r_a + r_p} \tag{1}$$

Applying geometrical ellipse features yield out the relations between semi major axis, apogee and perigee as:

$$r_p = a(1 - e) \qquad (2)$$

$$r_a = a(1 + e) \qquad (3)$$

both, r_p and r_a are considered from the Earth's center. Earth's radius is $r_E = 6378 \, \text{km}$. Then, the highs of perigee and apogee are:

$$h_p = r_p - r_E \qquad (4)$$

$$h_a = r_a - r_E \qquad (5)$$

Orbits with zero eccentricity are called *circular orbits*. The circularity of the orbit simplifies the mathematical analysis, since then it is:

$$e = 0 \Rightarrow r_a = r_p = a \qquad (6)$$

The movement of the satellite within its circular orbit is represented by *orbital time, radius, altitude* and *velocity*. Circular orbits are presented in Fig. 4, and mainly are categorized as:

• GEO (Geosynchronous Earth Orbits)
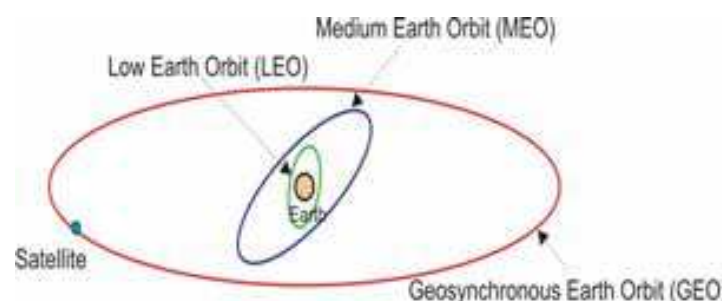• MEO (Medium Earth Orbits) and
• LEO (Low Earth Orbits)

Fig. 4. Satellite orbits

3.1 Orbit and ground station geometry
In Fig. 5, the position of a satellite within inclined orbital plane with respect to the ground station is presented (Cakaj, 2008). The Earth rotates from East to West. This is known as *eastward direction*, the opposite is called *westward direction*. An orbit in which satellite moves in the same direction as the Earth's rotation is known as *prograde* or *direct orbit*. The inclination of a prograde orbit always lies between 0º and 90º (consider Fig. 2). Most satellites are launched in a prograde orbit because the Earth's rotational velocity provides part of the orbital velocity with a consequent saving in launch energy (Maral & Bousquet, 2002; Richharia, 1999; Roddy, 2006).
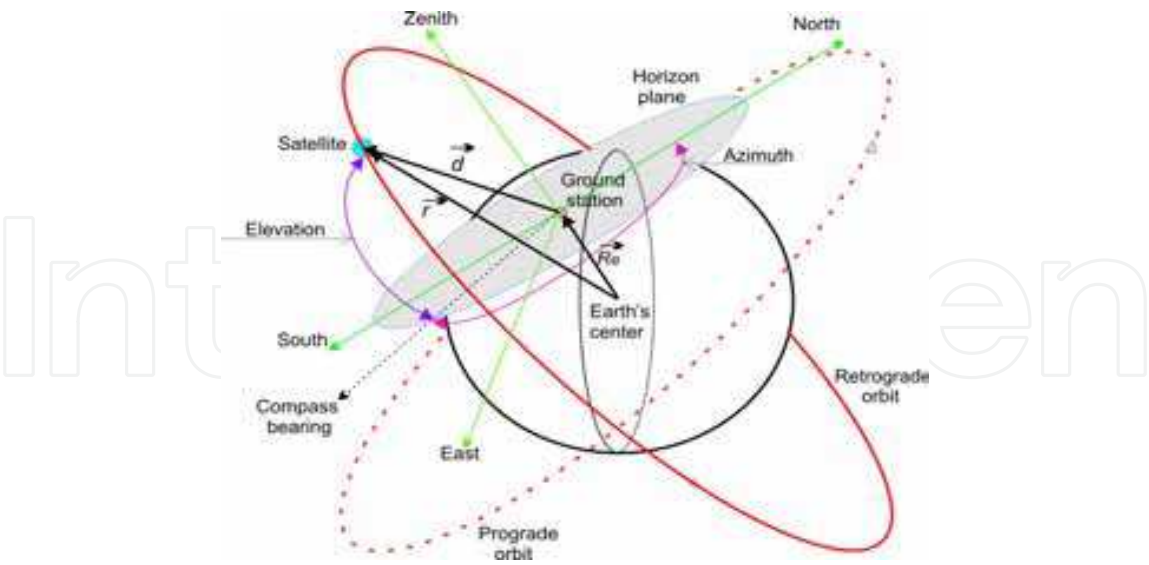
Fig. 5. Orbit and ground station geometry

An orbit in which the satellite moves in opposite direction to the Earth rotation is called *retrograde orbit*. The inclination of a retrograde orbit always lies between 90º and 180º. The position of the satellite within its orbit considered from the ground station point of view is defined by *Azimuth* and *Elevation* angles as presented in Fig. 5 (The *Azimuth* is the angle of the direction of the satellite, measured in the horizon plane from geographical north in clockwise direction. The *Elevation* is the angle between a satellite and the ground station horizon plane). From Fig. 5 yields:

$$\vec{d} = \vec{r} - \vec{R}_e \qquad (7)$$

where, $\vec{r}$ is the satellite radius vector, $\vec{R}_e$ ground station radius vector and $\vec{d}$ is the satellite to ground station range vector.

Theoretically, the position of the orbit is fixed in space (or slowly varying), while the location of the ground station rotates with the Earth. Because of the Earth's motion the satellite's coverage areas on Earth change, especially for LEO satellites which move too fast over the Earth, as it is presented in Fig. 6 (http://www.noaa.gov, 2005).
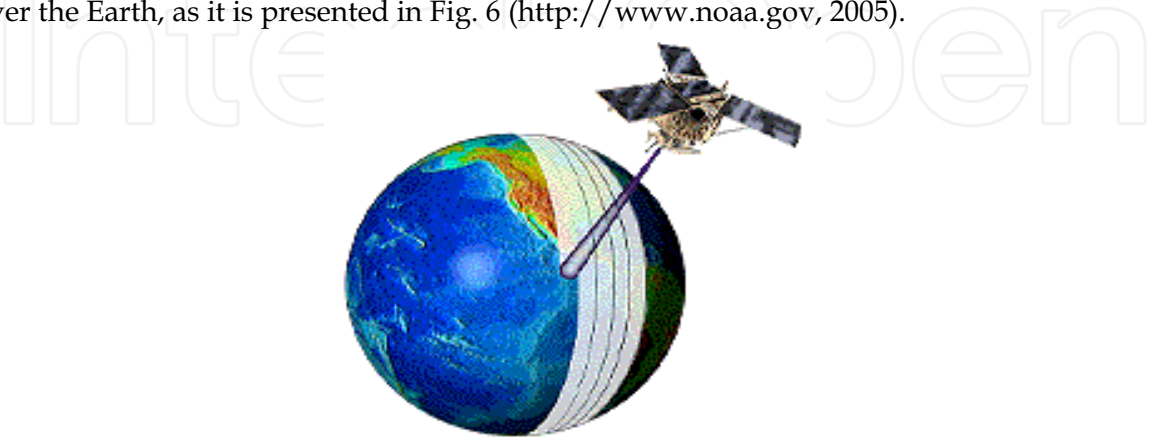

Fig. 6. LEO satellite and coverage area

The main goal is to establish the communication between the satellite and the ground station. Since LEO satellites move too fast over the ground station, then the communication between the satellite and ground station depends on how long the satellite can be seen from the ground station. This in fact brings the problem on finding the look angles and range of the satellite from the ground station (refer to Fig. 5) (Roddy, 2006; Cakaj et al., 2007). Further, this is clarified through Fig. 7.
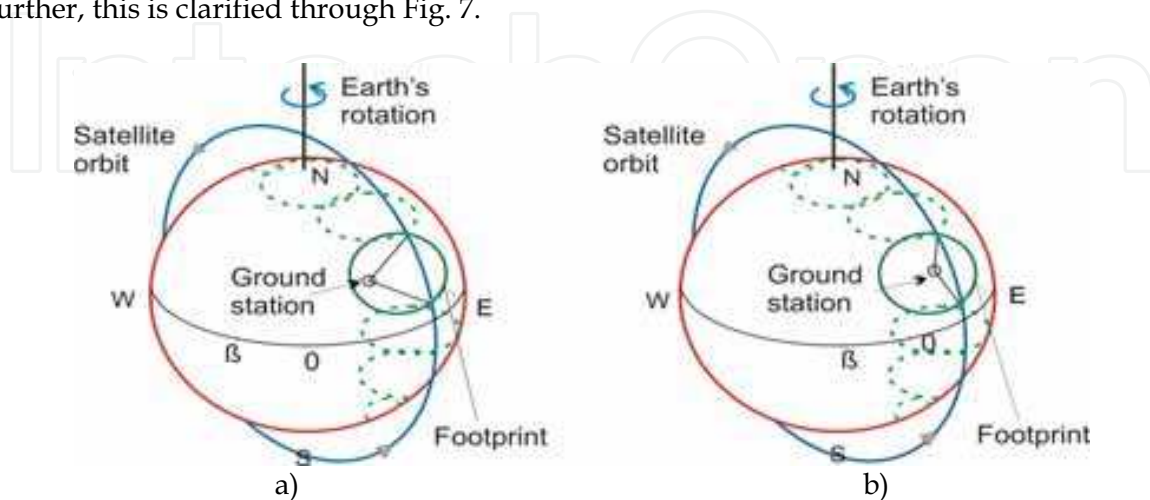

Fig. 7. Satellite passes for an Earth rotation angle of β per orbit

Because of Earth's rotation around its N-S axis for angle β the ground station changes the position relatively to orbital plane, so the pointing (azimuth and elevation angles) from the ground station to the satellite is not identical for the both satellite passes (see a) and b) in Fig. 7). Hence the communication duration between the satellite and the ground station is not constant and varies for each path over the ground station (Cakaj et al., 2007).

4. Artificial satellites

An artificial satellite is manufactured object dedicated to continuously orbit the Earth, or other body in space. The original objectives of artificial satellites were to serve low-cost communication relays and to provide new opportunities on investigation and development of new radio techniques.
Recently, especially with escalating cost of large satellites, attention is turned to smaller satellites so called *microsatellites*, which are taking also a new role, including science missions (Karoll et al., 1998).
An artificial satellite essentially consists of two main functional units: *payload* and *bus (platform)*. The primary function of the *payload* is to provide communication by repeater and antenna system. The *bus* provides all the necessary electrical and mechanical support to the payload. The bus consists of several subsystems. An artificial satellite (space segment) is presented in Fig. 8 (http://www.noaa.gov).

Fig. 8. Artificial satellite

Every satellite (especially, microsatellite when is dedicated for scientific purposes) carries special instruments that enable it to perform its mission (for example, a satellite that studies the universe has a telescope, a satellite that helps forecast the weather carries cameras to track the movement of clouds) (Essex et al., 2007; Grillmayer, 2004). There are six main types of artificial satellites, classified as follows (Oberright, 2004; Parrington, 1991).

- *Scientific research satellites*
- *Weather satellites*
- *Communications satellites*
- *Navigation satellites*
- *Earth observing satellites*
- *Military satellites*

Scientific research satellites gather data for scientific purposes. These satellites during performing their missions gather information about the composition and effects of the space around the Earth, record changes in Earth and its atmosphere and, still others observe planets, stars and other distant objects. Most of these satellites operate in low altitude orbits (LEO). Scientific research satellites also orbit other stars and planets (Mars, Moon, etc). Usually, these satellites communicate with ground stations in S-band.

Weather satellites are dedicated for analyses related to weather forecast. Weather satellites observe the atmospheric conditions over large areas. Their instruments measure cloud cover, temperature, air pressure, precipitation etc. Most of these satellites operate in low altitude orbits (LEO) and in S-band. These satellites always observe the Earth at the same local time. These weather data collected under constant sunlight conditions, then can be easier compared.

Communication satellites serve as relay stations, receiving radio signals from one location and transmitting them to another. A communication satellite can relay several television programs or very large number of telephone calls, and data services at once. Communication satellites are usually launched in a high altitude; such is geosynchronous orbit (GEO).

Navigation satellites enable operator of aircraft, ships, and land vehicles anywhere on Earth to determine their location with high accuracy. The satellites send out radio signals that are picked up by a computerized receiver carried on aircrafts, ships, or land vehicles.

Navigation satellites operate in networks in medium and low Earth orbits (MEO & LEO). *Earth observing satellites* are used to map and monitor our planet's resources and ever-changing chemical-biological life. They follow LEO orbits. Under constant illumination from the Sun, they take pictures in different colors of visible light and non-visible radiation. Scientists use Earth observation satellites to locate mineral deposits, determine the location and size of freshwater supplies identify sources of pollution and study its effects, etc. (Oberright, 2004; Parrington, 1991).

Military satellites include weather, communications, navigation and Earth observing satellites used for military purposes.

4.1 Low Earth Orbit (LEO) satellites

LEOs are just above Earth's atmosphere, where there is almost no air to cause drag on the satellite and reduce its speed. Less energy is required to launch a satellite into this type of orbit than into any other orbit (Richharia, 1999). Satellites that point toward deep space and provide scientific information generally operate in this type of orbit. The Hubble Space Telescope, for example, operates at an altitude of about 610 km with an orbital period of 97 minutes (Difonzo, 2000). LEO altitudes range from 275km up to 1400km limited by Van Allen radiation effects (sensors, integrated circuits and solar cells can be damaged by this radiation) (Zaim, 2002). Satellites in these orbits have an orbital period of around (90-110) minutes. For satellites this is a short flyover period, which means that the antenna at the ground station must follow the satellite very fast with high pointing accuracy. The communication duration time between the satellite and the ground station takes (5-15) minutes 6-8 times during the day (Zee & Stibrany, 2000; Keim & Scholtz 2006). Mismatch in pointing will lead to a decrease of received signal strength and further to a reduction of the communication quality.

LEO satellites have very wide applications, from remote sensing of oceans, through analyses on Earth's climate changes, Earth's imagery with high resolution or astronomical purposes. These satellites provide opportunities for investigations for which alternative techniques are either difficult or impossible to be applied by means on Earth.

4.2 Constellation

The constellation is a system of low (medium) Earth orbit (LEO or MEO) identical satellites, launched in several orbital planes with the orbits having the same altitude. The satellites move in a synchronized manner in trajectories relative to Earth. The application of low Earth orbit satellites organized in a *constellation* is an alternative to wireless telephone networks. Satellites in low orbits arranged in a constellation, work together by relaying information to each other and to the users on the ground.

In case the satellites within a constellation are equipped with advanced on-board processing, they can communicate directly with each other by line of sight using inter-satellite links (ISL). If the ISL is between satellites in the same orbit, it is called intra-plane ISL, and if it is between satellites in adjacent planes it is called inter-plane ISL (Difonzo, 2000). The GPS (Global Positioning System) constellation is presented in Fig. 9 (htpp://www.gps.gov). This constellation is organized in 6 orbital planes of 4 satellites per plane (24 satellites). Each satellite circles the Earth twice a day.
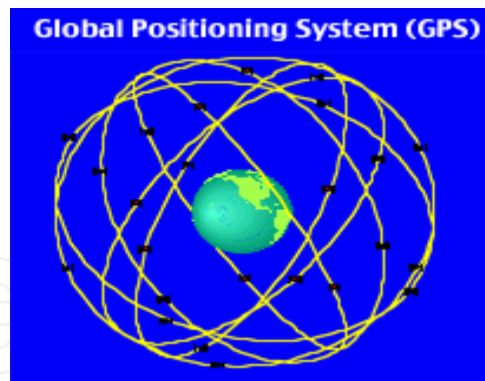
Fig. 9. GPS constellation

5. General aspects of interference

Interference may be considered as a form of noise. Effects of interference must be assessed in terms of what is tolerable disturbing level to the end user receiver. Interference effect to the end user receiver will depend on the amount of frequency overlap between the interfering spectrum and the wanted channel passband. From the technical and practical point of view, the following classification of interference should be considered (Richharia, 1999). These two scenarios in Fig. 10 are presented.

▪ *Co - channel interference*
▪ *Out - of - band interference*

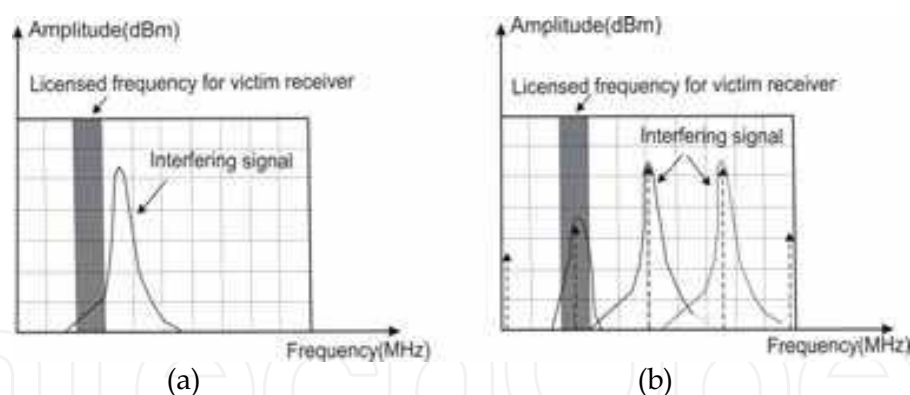(a)   (b)
Fig. 10. Co-channel interference (a), and out - of - band interference (b)

The receiver hit by interference is called *victim* receiver. The *co-channel interference* occurs when the victim receiver is disturbed by the system or equipment operating at the same frequency as the victim receiver. This is caused by unexpected legal or illegal (unlicensed) signals. Applying strictly the ITU recommendations on emitted power and frequency planning it is possible the co-channel interference to be controlled and minimized. More problematic is *out-of-band interference*. This interference occurs when the victim receiver is hit by signals which are generated by equipment which does not operate in the same frequency as the victim receiver. The phenomenon of generating other signals from one or more signals is called *intermodulation* (Richharia, 1999).

These new generated signals can unexpectedly fall within a victim receiver licensed passband (Fig. 10b). In case the generated intermodulated signal is too strong, it will not only interfere but it could completely block the desired receiving signal (Cakaj, et. al., 2005) Through modelling process, the problem can be analyzed and avoided in advance.

5.1 Intermodulation interference

In satellite communication systems the intermodulation noise is generated by nonlinear transfer characteristics of devices. Toward the uplink, the intermodulation noise is mainly generated because of the high power amplifier (HPA) nonlinearity. Related to downlink performance, especially in urban areas (presence of GSM, UMTS, WiFi, WiMax networks) intermodulation should be considered because of the low noise amplifier (LNA) nonlinearity. Disturbance introduced due to nonlinearity is known as *intermodulation interference.* These interference sources are statistically independent.

The nonlinear transfer characteristic may be expressed as a Taylor series which relates input and output voltages (Roddy, 2006).

$$e_0 = ae_i + be_i^2 + ce_i^3 + ... \tag{8}$$

Here, a, b, c, and so on are coefficients depending on the transfer characteristic, e_0 is the output voltage, and e_i is the input voltage, which consists of the sum of individual carriers. Intermodulation interference components can be classified as:

▪ *Harmonic Products*
▪ *Intermodulation Products*

Harmonic products are single tone distortion products caused by device nonlinearity. When a non-linear device is stimulated by a signal at frequency f_1, spurious output signals can be generated at the harmonic frequencies $2f_1$, $3f_1$... Nf_1. The order of the harmonic products is given by the frequency multiplier; for example the second harmonic is second order product. Harmonics are usually measured in dBc, which means dB below the carrier (fundamental) output signal.

Intermodulation products are multi-tone distortion products that result when two or more signals at frequencies f_1, f_2, ... f_n are present at the input of a nonlinear device. The spurious products which are generated due to the non-linearity of a device are related to the original input signals frequencies. Analysis and measurements in practice are most frequently done with two input frequencies. The frequencies of the two-tone intermodulation products are (Anritsu, 2000) :

$$Mf_1 \pm Nf_2 \text{ where } M, N = 0,1,2,3,.....$$

The order of the distortion product is given by the sum *M+N*. The second order intermodulation products of two signals at f_1 and f_2 would occur at $f_1 + f_2$, $f_2 - f_1$, $2f_1$

and $2f_2$. The third order intermodulation products (component ce_i^3 of Eqn. 8) of the two signals at f_1 and f_2 would be $3f_1$, $3f_2$, $2f_1+f_2$, $2f_1-f_2$, f_1+2f_2 and f_1-2f_2. These are presented in Fig. 11 (Anritsu, 2000).

Mathematically intermodulation product calculation could result in "negative" frequency, but it is the absolute value of these calculations that is of concern. Broadband systems may be affected by all non-linear distortion products. Narrowband circuits are only susceptible to those in the passband. Bandpass filtering can be an effective way to eliminate most of the undesired products without affecting in band performance (see Fig. 11), but third order of intermodulation products are usually too close to the fundamental signals to be filtered out.
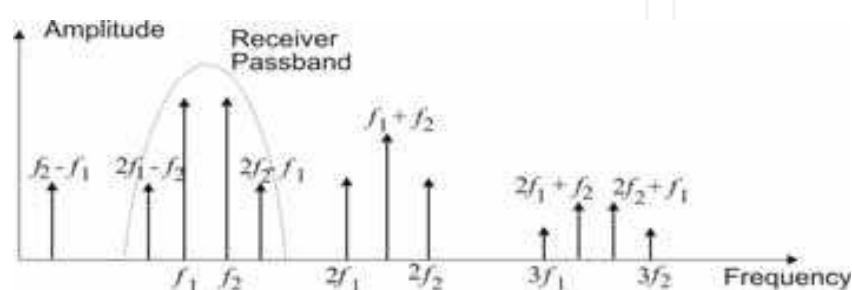

Fig. 11. Second and third order intermodulation products

Thus, the third order (and to a lesser extent fifth order) products contribute the major proportion of the intermodulation noise power. The closer the fundamental signals are to each other, the closer third intermodulation products will be to them. Filtering becomes very hard if the intermodulation products fall inside the passband. These unwanted intermodulation products can occur in receivers and may coincide with the operating frequency of the receiver in which case the wanted signal can be masked. The level of these products is a function of the *power received*. Further, out-of-band intermodulation products transmitted from the ground stations or satellites result in interference to other systems, also. To minimize such harmful emissions, international radio regulations restrict such out-of-band transmissions from ground stations to very low levels (Maral& Bousquet, 2002; Richharia, 1999; Roddy, 2006).

5.2 Intermodulation interference by uplink signal

The quality of communication depends on satellite ground stations performance. (Elbert, 2000; Landis & Mulldolland, 1993). The performance of a ground station could be disturbed by intermodulation interference because of permanent presence of uplink signal and any other RF (radio frequency) signal present in front end of receiving system. At ground stations located in urban areas with high density of mobile radio systems it is not easy to eliminate intermodulation interference signals since these are unpredictable. Each specific case specifically should be studied with on site respective experimental investigations.

Satellite ground station in urban area should be designed so that, at the receiver input, the level of the signal received from the satellite via the main beam of the ground station antenna exceeds the in-band noise by an adequate margin. But, the unwanted out-of-band inputs, as intermodulation products, generated by the ground station uplink signal and any

other radio frequency signal in front of low noise amplifier (for example: signals from nearby mobile system base stations), even though they are received via sidelobes in the ground station's antenna pattern, they could be higher and mask the wanted signal (Cakaj, et. al. 2008). Thus, within this chapter the interference of intermodulation products caused by uplink signal and any other radiofrequency signal present in the front end of the ground station's receiving system is analyzed and then modelled. Modelling process approach is an attempt as much as possible to generalize the case and based on that to make conclusions in advance before final decision on location, operation frequency up to device selection for the ground satellite station implementation.

In Fig. 12 it is presented the experiment set up which enables to check the intermodulation disturbance at the receiving satellite ground station. The double antenna ground station system is considered in order to clearly show up the presence of uplink signal. In Fig. 12, in front end, the GSM 1800 signals are considered, since they are close to S-band which is usually used for communication with LEO satellites. The similar procedure could be used in case of any other radio signal presence, also (Cakaj, et. al. 2005; Cakaj, et. al. 2008).
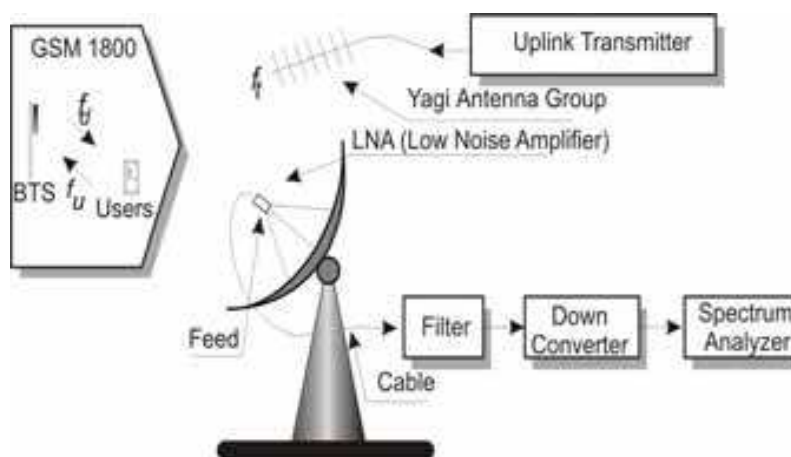

Fig. 12. Intermodulation scenario at satellite ground station

The presence of intermodulation products, at ground station, near the downlink frequency f_r caused by GSM 1800 and uplink signal f_t are expected because of eventual non-linearity of the Low Noise Amplifier (LNA) used in the front end at the downlink of the ground station. By the non-linearity of the low noise amplifier, the intermodulation products will be generated from the uplink signal at frequency f_t on one hand and GSM signals at frequencies (f_u, f_d) on the other (Cakaj, et.al., 2005).

Based on ITU-R F.382-6 (1.7GHz - 2.1GHz) frequency band for mobile systems at 1710MHz - 1785MHz is for the uplink and at 1805MHz - 1880MHz is for the downlink. The last channel frequency for uplink is 1781.4 MHz and for downlink it is 1876.4 MHz. The difference between the upper edge of the band and the last frequency within a band is called *Guard Band* (GB). Therefore, in our case the Guard Bands are:

$$GB_u = 1785MHz - 1781.4MHz = 3,6MHz \qquad (9)$$

$$GB_d = 1880MHz - 1876.4MHz = 3,6MHz \qquad (10)$$

For a particular case, considering uplink transmit frequency $f_t = 2055\,\text{MHz}$ and downlink receive frequency $f_r = 2232\,\text{MHz}$, signals present at the front-end of the low noise amplifier (LNA) of the receiving system at the ground station are presented in Fig. 13 (Cakaj, et. al., 2005).
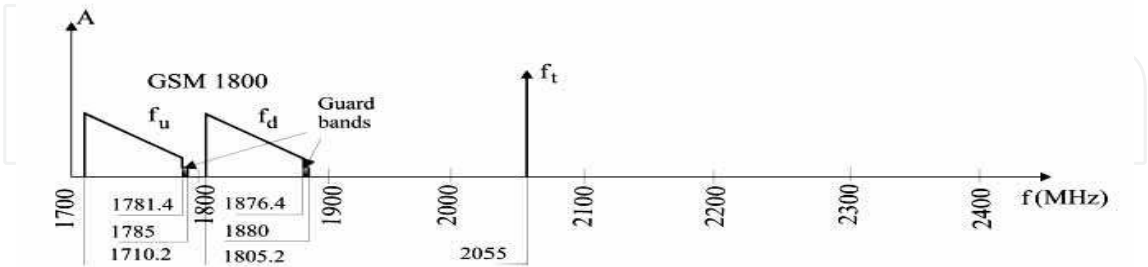

Fig. 13. Signals present at frontend (LNA) of the downlink

In order to clarify process, the first, few medium and the last one GSM 1800 channels with respective uplink f_u and downlink f_d signal frequencies are presented in Table 1.

Channel	f_u	f_d
512	1710.2MHz	1805.2MHz
521	1712.0MHz	1807.0MHz
523	1712.4MHz	1807.4MHz
586	1725.0MHz	1820.0MHz
632	1734.2MHz	1829.2MHz
868	1781.4MHz	1876.4MHz

Table 1. Frequency table of GSM 1800 uplink and downlink signals

Intermodulation products generated by signals at frequencies f_t and f_u fall too far on the frequency domain from the receiver's downlink frequency f_r, therefore they will not be treated. Third order intermodulation products generated by frequencies f_t and f_d are $2f_t \pm f_d$ and $2f_d \pm f_t$. Products $2f_t - f_d$ are worth further analysis, because they are only ones which fall in the frequency domain near the receiver's frequency f_r. These intermodulation products which appear at the LNA's output (respectively at the filters input) in frequency domain (RF) are presented in Table 2 (based on Table 1) and further in Fig. 14.

f_t	f_d	$2f_t - f_d$
2055MHz	1805.2MHz	2304.8 MHz
2055MHz	1807.0MHz	2293.0MHz
2055MHz	1807.4MHz	2292.6 MHz
2055MHz	1820.0MHz	2290.0 MHz
2055MHz	1829.2MHz	2280.8 MHz
2055MHz	1876.4MHz	2233.6 MHz

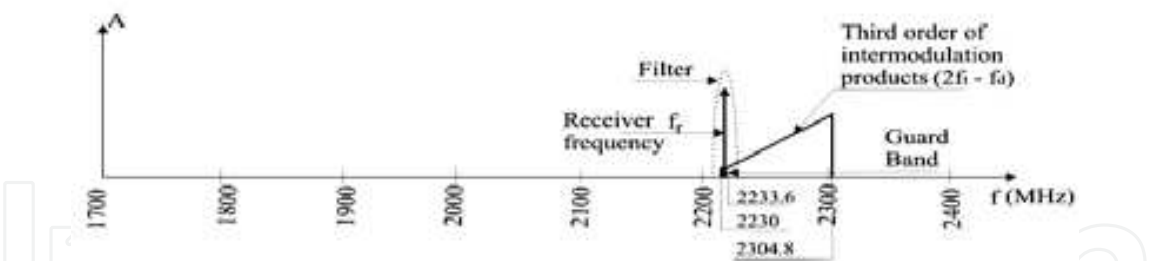Table 2. Third order intermodulation products

Fig. 14. Third order of intermodulation products

These signals will be faced with filter before going into the downconverter (see Fig. 12). The situation behind the filter and in front of the downconverter is presented in Fig. 15.

Fig. 15. Signals in front of downconverter

From Fig. 15 it is clear that the filter has substantially attenuated a considerable number of interference contributions from intermodulation products. Let us consider local oscillator frequency of the downconverter as f_{LO} = 2372MHz. If all signals presented in Fig. 15 in RF domain mirror into IF domain (intermediate frequency is 140MHz) with frequency f_{LO}, the spectrum in Fig. 16 follows (Cakaj, et. al. 2005). From Fig. 16 it is obvious the presence of intermodulation products behind the downconverter and in front of the demodulator as well. The question is: are these products disturbing the desired signal!
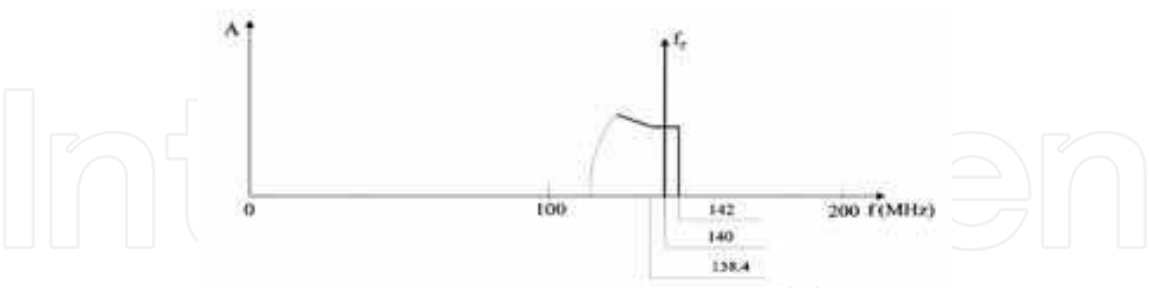

Fig. 16. Downconverter output

Further considering IF frequency as $f_{IF} = 140\,\text{MHz}$ and the receiving bandwidth $B = 100\,\text{KHz}$, than at IF output of the downconverter or as IF input of the demodulator, the bandwidth is:

$$139.95\text{MHz} < f < 140.05\text{MHz} \tag{11}$$

From Table 2 the intermodulation products (third column) are mirrored in IF band by local oscillator of frequency 2372MHz. The mirrored intermodulation products are: 67.2MHz, 79MHz, 79.4MHz, 82 MHz, 91.2MHz and 138.4MHz. No one of these intermodulation products fall within a frequency range under Eqn. 11, so there is no intermodulation interference. The upper edge of the frequency which can eventually disturb is 138.4MHz which one for the case of bandwidth of 100 KHz is too far in IF frequency domain. For the particular case above discussed, the receiving bandwidth of few 100 KHz will still be safe.

5.3 Interference modelling

Generally, if spurious signals generated as intermodulation products behind low noise amplifier *fall within a passband* of a receiver and *the signal level is of sufficient amplitude*, it can degrade the performance of the receiver. So, the receiver's operation will be disturbed if two above conditions are fulfilled. Based on this concept, and the above discussed particular case, it is built the intermodullation interference modelling which enables the interference calculation caused by any radio source of frequency f_x and satellite uplink signal of frequency f_t (Cakaj, et. al., 2008). Only third order of intermodullation products is considered. Among third order of intermodullation products are considered only components of frequencies $2f_x - f_t$ and $2f_t - f_x$. Fig. 11 and Fig. 16 tell us that these products could fall within a receiver's passband. Other intremodullation products of frequencies, $3f_x$, $3f_t$, $2f_x + f_t$ and $2f_t + f_x$ usually fall too far from the passband and practically are eliminated by filtering. Thus these products are not treated in modelling concept.

The amplitudes of intermodullation products of frequencies $2f_x - f_t$ and $2f_t - f_x$ are respectively $3A_x^2 A_t$ and $3A_t^2 A_x$, (these yields out from trigonometry) where A_x is amplitude of any radio signal of frequency f_x in front of low noise amplifier which is potential to cause intermodulation with uplink satellite signal of frequency f_t and amplitude A_t. Thus, third order of intermodullation products is characterized by:

$$f_{i1} = 2f_x - f_t, N_{i1} = 3A_x^2 A_t \qquad (12)$$

$$f_{i2} = 2f_t - f_x, N_{i2} = 3A_t^2 A_x \qquad (13)$$

where f_{in} is intermodualtion interference frequency of amplitude N_{in} for $n = 1,2$ behind the low noise amplifier. Since, the analyses are related mainly to the frequency domain, in order to simplify the case it is supposed that there is no amplification on overall system chain. Usually, the amplitude A_x is too low in front of low noise amplifier since it is limited by ITU rules about radiated power and consequently it is expected that the amplitude $N_{i1} = 3A_x^2 A_t$ will not disturb the receiver. The most dangerous component is $N_{i2} = 3A_t^2 A_x$ since the amplitude A_t is of high level because this is amplitude of uplink signal which has to overcome too high attenuation toward the satellite. The reference checking point is downconverter's IF output or demodulator's IF input. So, the intermodulation interference

is checked around intermediate frequency f_{IF}. The mirroring into intermediate frequency is achieved by downlink local oscillator frequency f_{LO}. All frequencies are mirrored by f_{LO}, including intermodulation products and desired receiving signal of frequency f_r. Thus, it is:

$$f_{IF} = f_{LO} - f_r \qquad (14)$$

For a receiver with bandwidth $B = 2\Delta f$, the receiving passband at IF input is from $f_{IF} - \Delta f$ up to $f_{IF} + \Delta f$ where f_{IF} is intermediate frequency which usually is 140MHz or 70MHz. Thus, the receiver could be disturbed if the intermodullation product mirrored at IF, falls within frequency band at IF input, mathematically expressed as:

$$f_{IF} - \Delta f \le f_{in} - f_{LO} \le f_{IF} + \Delta f \qquad (15)$$

By substituting f_{IF} form Eqn. 14 to Eqn.15 yields out,

$$(f_{LO} - f_r) - \Delta f \le f_{in} - f_{LO} \le (f_{LO} - f_r) + \Delta f \qquad (16)$$

Then further, if we substitute f_{in} from Eqn. 12 and Eqn. 13 at Eqn. 16 will have:

$$(f_{LO} - f_r) - \Delta f \le (2f_x - f_t) - f_{LO} \le (f_{LO} - f_r) + \Delta f \qquad (17)$$

$$(f_{LO} - f_r) - \Delta f \le (2f_t - f_x) - f_{LO} \le (f_{LO} - f_r) + \Delta f \qquad (18)$$

Thus, if frequency f_x of external radio source fulfills the Eqn. 17 or Eqn. 18 the desired signal at the receiver could be masked by intermodulation interference. The above concept is presented through flowchart in Fig. 17 (Cakaj, et. al. 2008). Input parameters in Fig. 17 are: f_x is frequency of any radio source in front of low noise amplifier of the satellite receiving system, f_t uplink transmit frequency, f_r is downlink receiving frequency and B is downlink receiver's bandwidth.

The level of respective signal should be compared with the level of desired signal at IF input. For comparison of these levels it is sufficient the relationship in between the relative values. Usually this is checked by measurement with spectrum analyzer at IF check point (refer to Fig. 12). The criteria for amplitudes comparison between the desired and interference signal depends on the Earth's station size and dedication. The criteria, between downlink carrier level and interference signal level ranges from 20 dB to 30dB (http://www.satsign.net/interfer.html). This is mathematically expressed by Eqn. 19, as:

$$S_{(IF)}(\text{dB}) - N_{in(IF)}(\text{dB}) \ge (20 \div 30)\text{dB} \qquad (19)$$

here $S_{(IF)}$ is desired signal power and $N_{in(IF)}$ intermodulation interference signal power at IF input. These two power levels can be calculated or measured in order to conclude about the receiver's disturbance as considered in flow chart in Fig. 17.
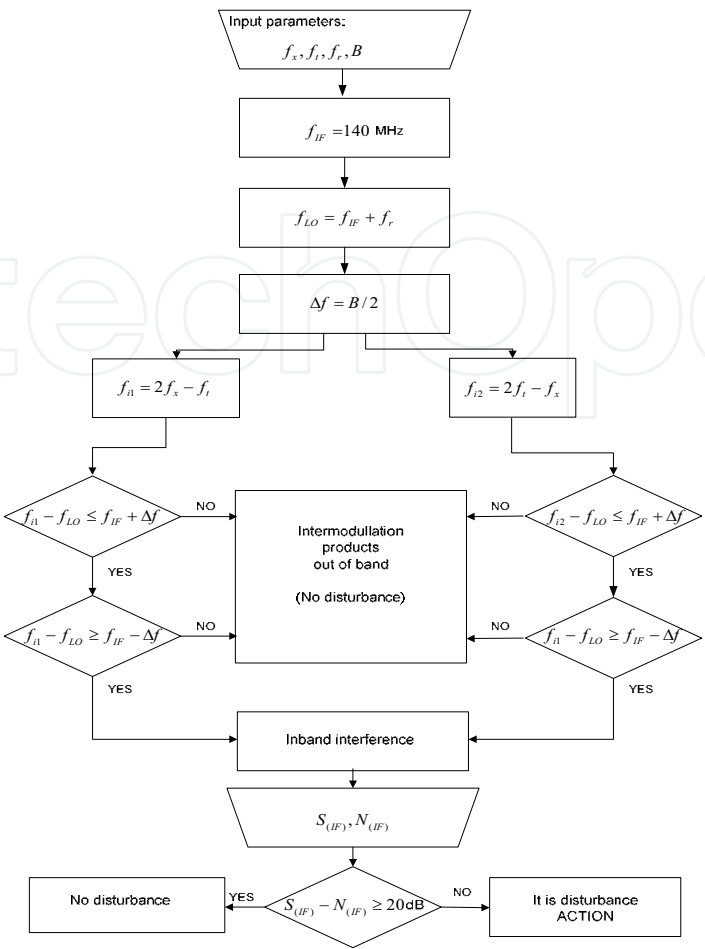
Fig. 17. Intermodulation interference modelling flowchart

Considering above flowchart it is structured intermodulation interference calculator presented in Fig. 18 (Cakaj, et. al., 2008).
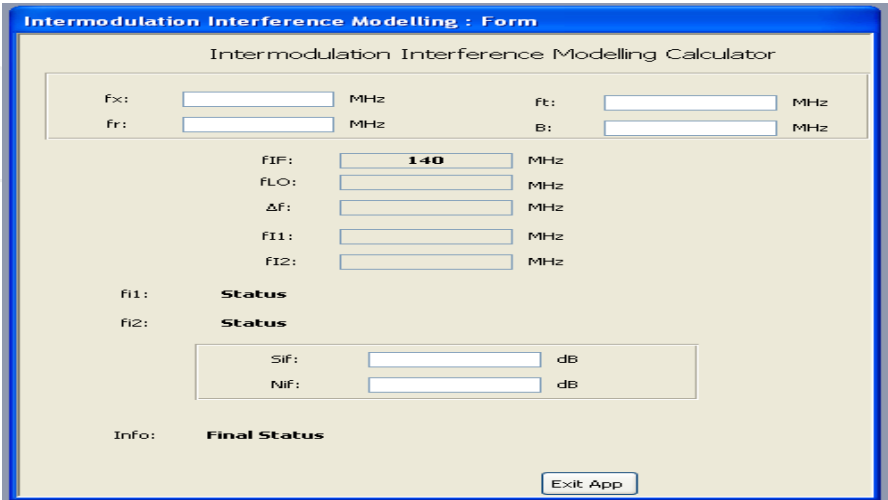

Fig. 18. Intermodulation interference calculator

Usually, only one of the treated components falls within a passband and cause the disturbance. So, if intermodulation components are out off band, then under **Status** (see Fig. 18) for f_{in}, $n = 1,2$ will show up this text: "*Intermodulation products out of band (no distrurbance)*", and no further analyses are needed. In case when one of components falls within a band, then under **Status**   for f_{in}, $n = 1,2$ will show up this text: "*In band interference*" and further analyses related to the amplitude level are needed. If amplitude of interference is under limited level at **Final Status** will show up text as, "*No disturbance*", and if the amplitude of interference level is above planned limit shows up the text: "*It is disturbance (Action)*". Based on the modelling concept, the intermodulation interference calculator is introduced. Applying this calculator, for the particular discussed case of the satellite ground station system with uplink transmit frequency $f_t = 2055$ MHz, downlink transmit frequency of $f_r = 2232$ MHz and bandwidth of $B = 100$ KHz, the intermodulation interference disturbs receiving system if in front of low noise amplifier is present signal of frequency $f_x = 1598$ MHz or $f_x = 2283.5$ MHz.

6. Conclusion

The performance of the ground station could be disturbed by intermodulation interference because of permanent presence of uplink signal. The reason behind intermodulation interference is eventual nonlinearity of low noise amplifier's transfer characteristic. Generally, if spurious signals generated as intermodulation products behind low noise amplifier fall within a passband of a receiver and the signal level is of sufficient amplitude, it can degrade the performance of the receiver. So, the receiver's operation will be disturbed. A methodology for analyzing the impact of intermodulation interference on reception performance has been described. These analyses are of high importance on the final decision of the ground station design. The introduced "intermodulation interference calculator" based on modeling concept could be applied on uplink signal frequency selection in order to avoid the interference. This methodology is applicable for MEO (Medium Earth Orbiting) systems, also.

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Modelling Simulation and Optimization

Edited by Gregorio Romero Rey and Luisa Martinez Muneta

Computer-Aided Design and system analysis aim to find mathematical models that allow emulating the behaviour of components and facilities. The high competitiveness in industry, the little time available for product development and the high cost in terms of time and money of producing the initial prototypes means that the computer-aided design and analysis of products are taking on major importance. On the other hand, in most areas of engineering the components of a system are interconnected and belong to different domains of physics (mechanics, electrics, hydraulics, thermal...). When developing a complete multidisciplinary system, it needs to integrate a design procedure to ensure that it will be successfully achieved. Engineering systems require an analysis of their dynamic behaviour (evolution over time or path of their different variables). The purpose of modelling and simulating dynamic systems is to generate a set of algebraic and differential equations or a mathematical model. In order to perform rapid product optimisation iterations, the models must be formulated and evaluated in the most efficient way. Automated environments contribute to this. One of the pioneers of simulation technology in medicine defines simulation as a technique, not a technology, that replaces real experiences with guided experiences reproducing important aspects of the real world in a fully interactive fashion [iii]. In the following chapters the reader will be introduced to the world of simulation in topics of current interest such as medicine, military purposes and their use in industry for diverse applications that range from the use of networks to combining thermal, chemical or electrical aspects, among others. We hope that after reading the different sections of this book we will have succeeded in bringing across what the scientific community is doing in the field of simulation and that it will be to your interest and liking. Lastly, we would like to thank all the authors for their excellent contributions in the different areas of simulation.

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