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Communication for Air Traffic Management (ATM) in Northern Areas

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Abstract: It is currently a significant ongoing effort worldwide to develop the future Air Traffic Management (ATM) system. As part of this work, a satellite communication system may ease the congestion problem for ATM services in high density airspace, and in addition provide coverage in oceanic, remote and polar (ORP) areas. For coverage over polar areas, satellites in highly elliptical orbits (HEO) are particularly suitable. In this paper the channel characteristics of an aeronautical satellite channel is considered. Both Molniya and Tundra orbits are included. Curves show how parameters like elevation angle, free space path loss and Doppler shift vary as function of satellite movements. In addition, atmospheric effects due to signal propagation through the ionosphere and the troposphere is considered, and finally the effect of multipath propagation due to signal reflections by the aircraft surface and ground.

Keywords: Satellite communication, channel characterization, multipath propagation.

1. Introduction

The amount of air traffic has increased significantly during the last decades. The Air Traffic Management (ATM) systems currently used have basically not changed during this time. Predicting a continued growth in the coming years, the amount of air traffic these systems can handle will soon be exceeded, in particular in high density airspace such as continental Europe. The result will be lower efficiency, more pollution and environmental damage, and reduced security. As a response to this challenge, the ATM community world wide, and in Europe and in the U.S. in particular, is investing significant effort to renew the ATM systems. SESAR (Single European ATM Research) [1] is a European program financed by the EC, EUROCONTROL and European industry created to implement this task. A similar program in the U.S. is called NextGen [2].

One part of the ATM system that needs to be renewed is the communication between aircraft and the traffic control on ground. Currently the aeronautical VHF-band is used for this type of communications, which is mainly voice, and it is close to saturated. Several new communication systems will therefore be developed for future ATM services, which will primarily be data services. One of these systems is based on the IEEE802.16 standard operating in the 5.1 GHz band for airport surface communication. Another one is a long distance L-band datalink system for communication between aircraft in the air and ground.

The European Space Agency (ESA) is collaborating with SESAR to develop a third system; a complementary satellite communication system. This is done in a separate program called Iris, and the system is planned to be operative in year 2020. Over continental Europe the satellite system may ease the capacity shortage, and over oceanic, polar and remote (OPR) areas it may increase the coverage by providing ATM services in areas out of reach of the terrestrial communication systems. The baseline satellite system will consist of two geostationary (GEO) satellites, providing the required level of quality and availability of an ATM system. A problem related to the geostationary satellite system is the lack of coverage at high latitudes. Therefore a constellation of satellites in highly elliptical orbits (HEO) is considered as an addition and complementary to the baseline GEO system. The expected user requirements of such a HEO system are considered in [3].

One alternative solution to provide ATM services in polar areas is use the Iridium system, which contains 66 fully operative satellites in polar orbits. Current users in polar areas do report problems related to low data rate and unreliable connections. Iridium has however plans to replace the current constellation with new satellites with improved bandwidth. Within the SESAR time span, Iridium may therefore be able to provide ATM services in polar areas with improved quality. This potential competition to a dedicated European HEO satellite system for ATM coverage in northern areas needs to be taken into account in the continuation of the Iris program.

In this publication the characteristics of the propagation channel for a 1.5 GHz system are investigate, including effects related to the particular highly elliptical orbits, atmospheric effects and multipath propagation due to reflections by the aircraft surface and ground reflections. The purpose of the publication is to highlight the particular requirements with respect to propagation conditions encountered for HEO communication systems in particular, and ATM and aeronautical services in particular. The results are limited to the L-band link between aircraft and satellite. Hence, the higher frequency feeder link between the satellite and the ground based gateway is not included.

2. Coverage Area

Geostationary satellites may provide coverage up to 74°N - 82°N. A natural transition between GEO and HEO coverage would however be placed further to the south, at 72°N-73°N. There is only one airport above this latitude, at Longyearbyen on Svalbard (located at 78°N). Air traffic above this latitude will therefore be mostly limited to cross polar routes. Currently four polar routes are defined between the North American continent and Asian countries such as Japan, China, India and Pakistan. There are currently in the order of 600-800 flights per months crossing the Arctic by one of these routes. Compared to the traffic over e.g. continental Europe, the amount of ATS communication is therefore modest.

In addition to the polar area, ATM over the Nordic counties (Norway, Sweden and Finland) may be included in the coverage area for a HEO satellite system. These countries are located far to the north (latitudes between 55°N and 78°N), and in particular Norway has a significant amount of domestic traffic towards its northern parts. As the main objective of the future ATM system will be to assure air traffic in denser airspace, different solutions may prove more efficient in these northern areas than further to the south. It is therefore a possibility to use HEO satellite communication for ATM services instead of investing in ground infrastructure in low populated areas far to the north, and for helicopter traffic to oil installations in the North Sea and Barents Sea (e.g. Shtokman field).

3. Propagation Channel

There are two types of orbits that may be employed for a HEO satellite system; Tundra and Molniya [4]. Both orbits have an inclination angle equal to 63.8°. In the late 1980s and early 1990s, work was done to characterise the propagation channel for HEO satellite system (see e.g. [5] and [6]). In this section this work is extended to aeronautical communications.

The Tundra orbit has a period of 24 hours. Hence, each time the satellite reaches the position the farthest away from the earth (apogee) it is over the same location on the earth surface. The apogee height is about 47 000 km (compared to the geostationary satellite height of 36 000 km). Examples of Tundra orbit satellites are the Sirius satellites providing satellite radio broadcasting over Northern America.

The Molniya orbit has a period of 12 hours. A Molniya satellite may therefore provide good coverage over both e.g. North America and Europe. The apogee height is 39 000 km. Russia currently has several satellites in Molniya orbits, both for military applications and for television broadcasting.

3.1 Effects of Orbiting Satellites

As opposed to GEO satellites, HEO satellites do not appear to be fixed, and both elevation angle and azimuth angle varies. In order to define the elevation angle ε it is convenient to define three vectors. $\mathbf{r_a}$ is the vector from the earth centre to the aircraft, $\mathbf{r_s}$ is the vector from the earth centre to the satellite, and $\mathbf{d} = \mathbf{r_a} - \mathbf{r_s}$ is the vector from the aircraft to the satellite.

The vectors are given in Cartesian coordinates by [6]:

$$\mathbf{r_a} = (R+h)(\cos L \cos\theta_a \ \mathbf{i} + \cos L \sin\theta_a \ \mathbf{j} + \sin L \ \mathbf{k}),$$

$$\mathbf{r_s} = \frac{A\cos I}{1+e\cos\theta_s}\cos\theta_s \ \mathbf{i} + \frac{A\sin\theta_s}{1+e\cos\theta_a}\mathbf{j} - \frac{A\sin I}{1+e\cos\theta_a}\cos\theta_s \ \mathbf{k} \,,$$

where R is the earth radius, h is the altitude of the aircraft, the angle L is the latitude of the earth station, the angle I is the inclination angle of the satellite orbit, e is the eccentricity of the satellite orbit, and A is equal to b^2/a. The parameter a is the semi-major axis and b the semi-minor axis of the satellite orbit. The angle from the perigee longitude is denoted θ, where sub-script s denotes elliptical satellite orbit and sub-script a circular earth station orbit. The elevation angle can then be calculated using the scalar product between $\mathbf{d}$ and $\mathbf{r_a}$:

$$\varepsilon = \frac{\pi}{2} - \Omega = \frac{\pi}{2} - \arccos\left(\frac{\mathbf{d}\cdot\mathbf{r_a}}{|\mathbf{d}||\mathbf{r_a}|}\right)$$

The elevation angle for a Tundra satellite and a Molniya satellite as function of the latitude of the receiver is shown in Figure 1. Both orbits provide good coverage for latitudes up to 90°N. Molniya orbit satellites provide coverage over the North Pole with minimum elevation angle above 20 degrees almost 18 hours a day, which is 7 hours more then Tundra orbit satellites. For the far north, Molniya orbit satellites may therefore provide better coverage than Tundra orbit satellites, while the opposite is the case for lower latitudes (less than about 60 degrees).

The free space path loss in dB is given by:

$$L_f = 20\log_{10}(d) + 20\log_{10}(f_c) + 92.44\,,$$

where d is the distance between the transmitter and receiver given in km and f_c is the carrier frequency in GHz. The free space path loss for Tundra and Molniya satellites is shown in Figure 2. The maximum free space path loss is in the order of 187-188 dB for Tundra satellites, and in the order of 185-186 dB for Molniya satellites. It does not vary significantly with the altitude or position of the earth station.

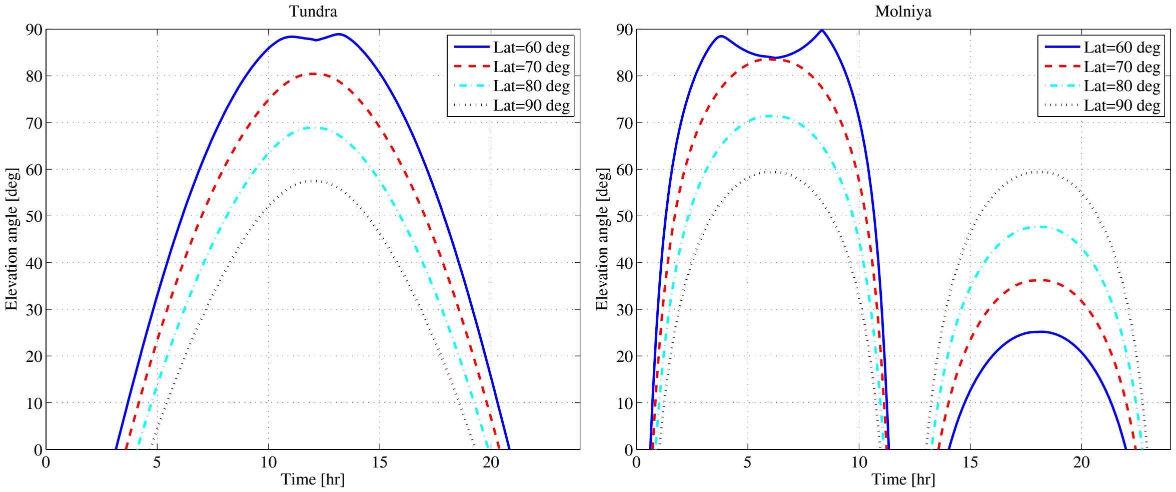

Figure 1Elevation Angle for HEO Orbits

The Doppler shift is related to the radial velocity v_d between earth station and satellite:

$$f_d = -\frac{v_d}{c} f_c$$

The radial speed can be calculated using projection:

$$v_d = \mathbf{v} \cdot \frac{\mathbf{d}}{|\mathbf{d}|} = \left(\frac{d\mathbf{r_s}}{dt} - \frac{d\mathbf{r_a}}{dt} \right) \cdot \frac{\mathbf{d}}{|\mathbf{d}|}$$

The maximum Doppler shift is in the order of 2 kHz for Tundra satellites and 8-9 kHz for Molniya satellites. The Doppler shift caused by the aircraft may be up to about 1 kHz. It must therefore be taken into account for communications with Tundra orbit satellites, while it is less significant for communication with Molniya orbit satellites.

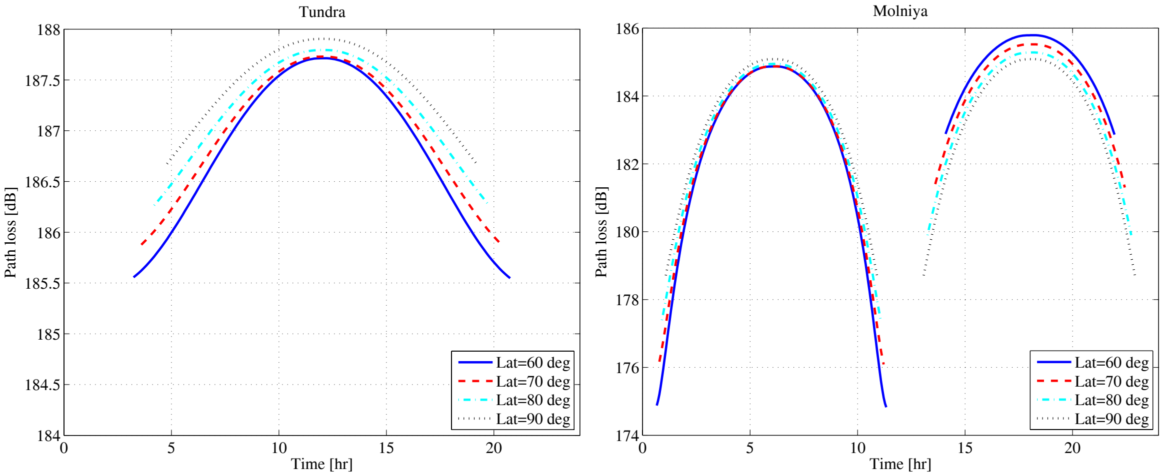

Figure 2 Free Space Path Loss

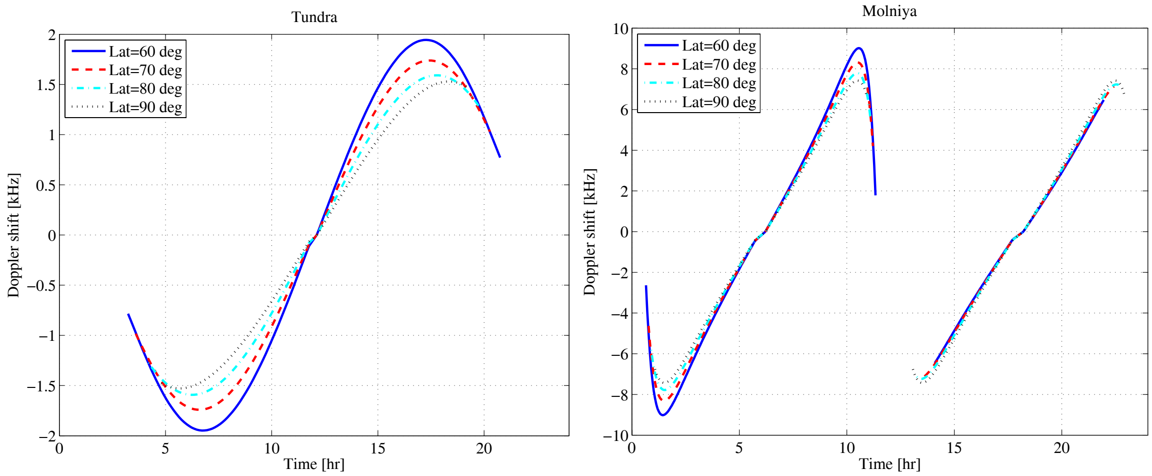

Figure 3 Doppler Shift

3.2 Atmospheric Effects

A signal propagating between an aircraft and a satellite will be affected by the ionosphere and the troposphere.

A signal propagating through the ionosphere is degraded due to background ionizations and irregularities. Background ionizations lead to Faraday rotation, group delay and dispersion, while irregularities lead to scintillations of the signal.

Background ionization depends on the total electron content (TEC) accumulated along the earth station-satellite signal path. One method used to estimate the TEC is based on the international reference ionosphere (IRI), another one is based on NeQuick. The main impact of background ionization is Faraday rotation. At 1.5 GHz, the Faraday rotation may vary from 0.01 rad to about 10 rad. The cross-polarization discrimination XPD in dB is related to the Faraday rotation angle by $XPD = -20\log(\tan\theta)$. Another effect of background ionizations is the group delay, which will generally be a fraction of a microsecond. The dispersion due to background ionization is however small, and can consequently be neglected for realistic signal bandwidths.

Small-scale irregular structures in the ionization density cause a steady signal to fluctuate in amplitude, phase and apparent direction of arrival. Such scintillations are particularly important at high latitudes and close to equator. In polar areas this may be as large as 5 dB at solar maximum. It is recommended that the global ionospheric scintillation model (GISM) is used to predict the intensity. The corresponding Doppler spread is about 0.1 Hz to 1 Hz. Compared to channel variations shifts due to aircraft and satellite movements, which may be in the order of kilohertz, these variations are slow.

Many of the tropospheric effects can be neglected for frequencies as low as 1.5 GHz. Dispersion due to background ionization will be small, less than 1 ns according to Figure 4 in Rec. ITU-R P531-9 assuming realistic signal bandwidths and TEC. It can consequently be neglected for realistic signal bandwidths.

The one tropospheric effect that may be of importance is the attenuation by precipitation and clouds. A general method to predict the attenuation along a propagation path is given in ITU-R P.618-9, and is based on maps over rainfall rate provided in ITU recommendations.

3.3 Multipath Propagation Due to Reflections

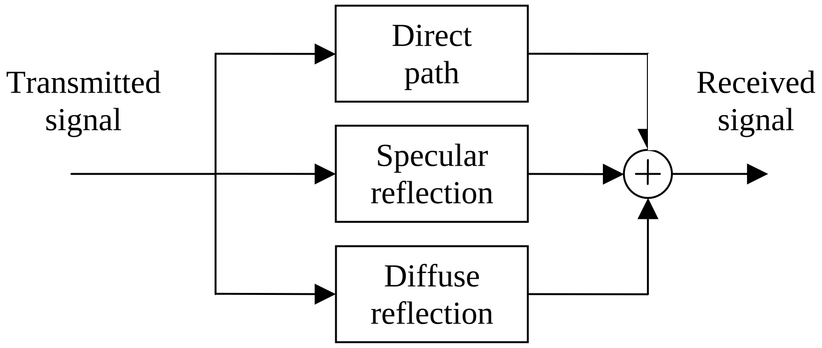

Figure 4 The three signal components in the aeronautical channel model

The channel variations due to satellite and aircraft movements and atmospheric effects vary slowly, and need to be taken into account in system design to assure the required QoS and availability. Variations due to multipath propagation caused by signal reflections vary much faster and need to be taken into account in the modem design in choosing coding and modulation techniques, channel estimation techniques etc.

Although other reflections may be imagined, the multipath components in a general aeronautical communications setting usually come from two sources, the aircraft itself and the ground. In [3], the authors undertook a measurement campaign to determine the effects of multipath reflections from the plane and the ground on satellite navigation and positioning. In addition to the channel measurements a set of simulations were performed using 3D ray tracing techniques. The conclusion from the work was that the reflections from the fuselage had an average delay of 1.5 ns, a relative power of -14.2 dB and a Doppler bandwidth of less than 0.1 Hz. The small average delay, which corresponds to an additional path length of about 50 cm, suggests that only reflections close to the antenna contribute to the received signal power. For relevant bandwidths, the reflected signal component will be incorporated in the direct signal component, i.e. leading to so-called narrowband fading. This fading process can be modeled using a Rice distribution. The Rice factor will depend on the incidence angle of the signal. As a worst case value 9 dB is recommended.

The delay of received signal reflected by the ground will be significantly longer, and will depend on the altitude of the aircraft and the satellite elevation angle. A recommended value to be used is 6-7 μs. The ground reflection will contain a specular component and a diffuse component as illustrated in Figure 4. The diffuse component may have a delay spread in the order of 3 μs. The Rice factor of the first ground reflection tap will depend on the antenna diagram and on the topology and Fresnel reflection coefficient of the ground. The other ground reflection taps can be modeled as Rayleigh distributed.

Ice and dry ground will lead to more severe fading than sea and wet ground. The difference in multipath power for different surfaces is illustrated in Figure 5. As a consequence, communication over the icy polar cap will be more affected by multipath propagation than communications further to the south.

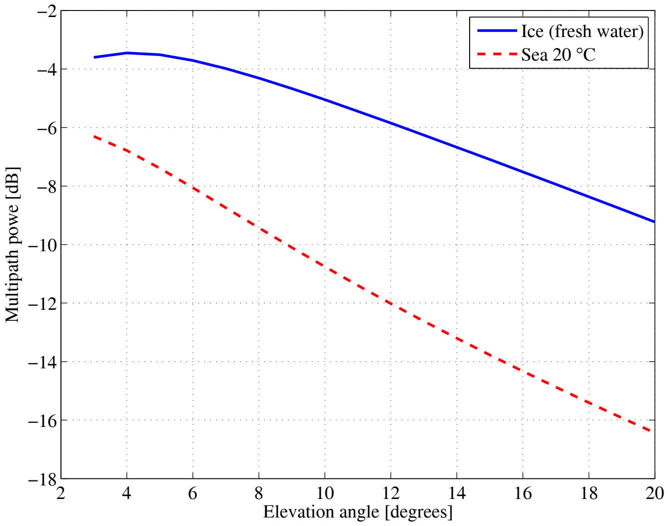

Figure 5 Signal power for ground reflections

4. Conclusions

In this publication propagation characteristics of a HEO satellite system for aeronautical communications in northern and polar areas have been assessed. The background for this work is the interest and need to design a satellite communication system providing the same level of ATM security over northern and polar areas as over the areas further to the south.

A HEO satellite constellation is in this respect one alternative solution, providing coverage up to 90°N. There are however other solutions such as the future Iridium Next. An important task of ESA's Iris program developing and implementing the future European satellite system for ATM services will therefore be to consider the business side of launching a dedicated European satellite system.

One particularity related to HEO systems compared to GEO systems is the movements of the satellites relative to ground. This movement induces variations in elevation angle and visibility, path loss and Doppler shift. These effects must be taken into account in the design of the satellite systems through link budget calculations and others. The atmospheric effects are different far to the north than further to the south, being more unpredictable than further to the south.

Concerning multipath propagation due to reflections, ground reflections will have longer delays than what is usual for ground based systems due to the difference in direct and reflected path lengths. The reflected component will in addition contain both a specular component and a diffuse component with a certain delay spread.

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