User Requirements for HEO SATCOM for ATM in High Latitudes

Jan Erik Håkegård, Trond Bakken, Tor Andre Myrvoll, SINTEF, Trondheim, Norway

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, an overview of user categories is given and the channel characteristics of an aeronautical satellite channel are 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.

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 particularly 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. In order to achieve globally interoperable and compatible solutions, coordination between SESAR and NextGen is necessary.

One part of the ATM system that needs to be renewed is the communication between aircraft and the air 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. 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 L-band communication system. The baseline satellite system covering Europe 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 system is planned to be operative in year 2020.

An alternative to a HEO system solution is to use a satellite system with Low Earth Orbit (LEO) satellites. Two operational systems are Iridium and Globalstar. The current systems are low rate, offering in the order of a few kilobits per second to users. Evolutions of the systems such as Iridium Next may however provide increased data rates

making them an interesting alternative for future ATM services.

In this publication an overview of user categories in northern and polar latitudes is given. The categories include scheduled flights, non-scheduled flights, general aviation, helicopter and military activity. Then the characteristics of the propagation channel for a 1.5 GHz system are investigated, 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.

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, in the area of about 68°N to 74°N. There is only one airport located above 74°N, at Longyearbyen on Svalbard (located at 78°N). Air traffic above this latitude will therefore be mostly limited to cross polar routes.

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 also a possibility to use HEO satellite communication for ATM services instead of investing in expensive 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).

User categories

The users of ATM services that may benefit from a HEO satellite system in these areas that can be grouped into a number of categories. These are described in this section.
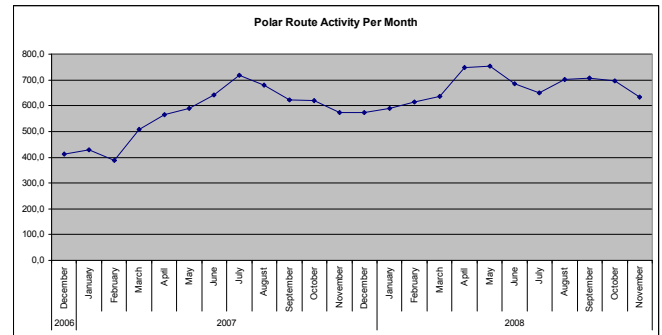
Scheduled activity

Figure 1 Number of cross polar flights/month

There is a steadily increasing volume of cross polar flights. Currently four polar routes are defined between the North American continent and Asian countries such as Japan, China, India and Pakistan. The website of the Cross Polar Working Group (CPWG) provides statistics of the number of cross polar flights. Fig. 1 shows the evolution over the last two years. The number of flights per month is in the order of 600-800, and the trend is that the number increases with time. Still, compared to the traffic over e.g. continental Europe, the amount of ATS communication in Arctic areas will be modest.

Concerning the Nordic countries, the population is small compared to continental Europe. However, in Norway with less than 5 million inhabitants there are more than 50 airports with scheduled traffic. Despite its small population base compared with the rest of Europe, the air travel market is considerable. Topographical and geographical conditions and long distances mean that air travel between several destinations is the sole possible means of transportation, in particular for business travel. In Scandinavia per capita air travel averages 3.2 trips per year, which is considerably more than the rest of Europe. Between the largest cities high speed train is an alternative to air travel, but the availability of high speed trains is still limited. There are however concrete plans to

invest in more high speed trains, especially in Sweden.

General Aviation (GA)

Due to a high standard of living, large land areas, geographically spread population and industry, aviation is one of the major forms of transportation in Norway, Sweden and Finland. This results in a high number of private owned aircraft used for own transportation or leisure.

In the northernmost county in Norway, Finnmark, there are some restrictions on GA activity, related to where it is allowed to land and a requirement to submit a flight plan. Still, there is some activity, and it is especially popular for tourists going by their own plane to North Cape, witch is at 71°N and the northern outskirt of the European continent. In Sweden and Finland there are GA activity related to hunting, fishing and hiking. The regulations are not as strict as in Norway.

Despite a relative high number of small aircraft involved in General Aviation, this category will pose very limited requirements on a satellite communication system, due to its low cost profile, light weight, limited budget for retrofits and often operating without the involvement of AOC and ATS.

Helicopter activity

The helicopter activity in the Scandinavian countries is large compared to the scarcely population. In Norway there are more than 200 helicopters operating within different branches. These activities are school flying, taxi flying, photo, advertisement, spraying, freight, and so on. But the main part of the Norwegian helicopter activity is passenger transportation between the main land and the continental shelf. Helicopters are the preferred means of transport for personnel to and from offshore installations due to their speed, convenience and flexibility of use, even during severe weather conditions. Apart from these considerations, helicopter transport is seen as healthier and less hazardous with regard to reduced travel sickness and easier personnel transfer onto an offshore location compared with ship transportation. The activity in the North Sea

includes crew change, in-field shuttle, and SAR services supporting many Norwegian oil and gas operations.

The helicopter activity in Finland, Norway, including Svalbard, and Sweden can be divided into three main areas;

- Operations related to the oil industry, which by far is the largest activity.

- Ambulance flying & SAR flying, border control and coastal guard.

- General helicopter operations including small scale passenger transport, aerial photography, surveillance, inspections, tourist transportation, reindeer husbandry, drop operations, advertisement and so on.

Military activity

The armed forces in the Nordic countries all have a substantial activity, but it is mainly the Royal Norwegian Air Force that operates in the northernmost areas. Over high seas in the oceanic north and in the polar region, armed forces from other nations occasionally have flights.

The total number of medium to large military aircraft in the three countries, including fighter aircraft, is more than 450, and there are about 170 military helicopters and 15 Unmanned Aerial Vehicles (UAVs).

There are in addition large and complex exercises with more than 100 participating aircraft, helicopters and UAVs every year within the area. Daily operations and exercises demand a considerable amount of CNS capacity, especially concerning network centric warfare principles.

Military CNS often operates within the civil spectrum using civil equipment, although some of the CNS specifications are military, e.g. with regards to reliability and security. Military aviation and civil aviation have different objectives, and hence different requirements. However, in the future, with the limited capacity within the civil sector there will be a need to operate in a coordinated way and with interoperable standards and equipment. To some extend, e.g. concerning use of airspace, this is taken care of through the Flexible Use of Airspace (FUA) concept and the

future implementation of the Single European Sky (SES).

Other activities

Norwegian Polar Institute

The Norwegian Polar Institute operates normally one to two helicopters in the Arctic from March to September. The helicopters operate from a research vessel or field camps at Svalbard (between 74˚ N and 81˚N). Main activities are concentrated around Svalbard, but stretches west towards Framstredet and east towards Novaja Semlja. The Institute expects new vessels with helicopter pads for medium size helicopters to be ready in 2012. This will increase the helicopter activity, especially into the Polar Basin.

Operationally the requirement is to relay the position of the aircraft beyond the horizon. Today, this is done by HF or Iridium satellite communication only with partial success. Reliable voice communication and real time automatic position tracking would be of great interest. With satisfactory bandwidth, which is not available today, the Institute suggests that there will be both operational and scientific interest in transmitting sensor data from the helicopter, for example live video reporting the ice condition of the sailing route, ice melt situation or number of seals on the ice.

With improved communications the Institute suggests that UAVs would be used for data collection and surveillance to a greater extend than today. Today Iridium is used to some extend, but it would be useful to have a more suitable satellite communication solution, e.g. for reprogramming of the UAV flight track.

Barneo base

The Barneo base is a Russian base on the drifting ice in the vicinity of the North Pole. In 2007 the base was located approximately 100 kilometers from the North Pole. The base has been set up regularly in the recent years, but because of the drifting ice, the base and runway needs to be prepared every season. The base is used by scientists and as a forward base for adventurers going to the pole. The runway serves aircraft up to the size of Antonov 74 for cargo and passengers. In conjunction to the base there is also quite a lot of helicopter activity, flying to the geographical North Pole and other places in the Arctic.

Northern Sea Route

The Northwest Passage and the Northeast Passage are getting ice-free and available for sea transportation from the Atlantic Ocean to the Pacific Ocean respectively along Northern America and the Russian Federation. This reduces the travel time considerably, but the climate and ice conditions are still very difficult. The increase in ship traffic will bring increased requirements for surveillance and search and rescue in the area. A substantial part of the increased surveillance and Search and Rescue will be done by air, and this may give raise to new demands for services and coverage in the northern and polar region.

Modified Automatic Dependant Surveillance (M-ADS)

Helicopter traffic over the North Sea is performed both in controlled and uncontrolled airspace over international waters. The lack of radar coverage makes the establishment of controlled airspace difficult. Based on several incidents and accidents in the helicopter traffic to and from oil installations along the Norwegian coast, and an impression that the safety was not up to what should be expected, two official Helicopter Safety Studies (Helicopter Safety Study 1 and 2) were conducted. The studies investigated risks and safety issues for the helicopter traffic related to the oil industry. Among the recommendations brought forward by the studies was to improve the communication between helicopter and ATS in areas outside radar coverage. A third study is initialized, and in addition to risk analyses and risk mitigation it will look at developments in traffic volume, use of new technology and consequences for helicopters for the period 2009 – 2020.

ADS is a cooperative system for air traffic control (ATC) and related services. M-ADS is a modified system developed by Kongsberg Defence & Aerospace (KDA) to improve the flight information and alarm services over the Norwegian continental shelf. M-ADS provide a complete surveillance of the helicopter traffic making the ATC able to follow the traffic in areas not covered by radar. M-ADS meets the ICAO directives for ADS, but is not certified for separation purposes.

M-ADS have been mandatory for helicopters regularly operating in the Norwegian sector at the continental shelf since 2002 (operational certification). The areas where the service is offered, ADS-Areas, lies within airspace class G. Aircraft without M-ADS are requested to fly outside these areas, but this is not mandatory.

Kongsberg Aerospace selected Racal Avionics Ltd as a team member to develop and produce M-ADS. The system, which comprises an ADS Unit and an INMARSAT Aero `L' Class 1 Low Gain system (SDU and HPA), provides the real-time performance necessary to support the integrity requirements of air traffic services. The system supports packet data services at data rates up to 1200 bps. Data-3 (ATN, X-25) services are supported via INMARSAT satellites. The communication protocols support ATS, AOC and Health and Usage Monitoring (HUMS) data transfer. Features include miniaturization for helicopter use, automatic log-on to INMARSAT system and automatic transport connection to ATC centre, selectable reporting intervals, Communication Management Unit (CMU) functionality, and global addressing.

The avionics in the aircraft is connected to the M-ADS unit, which again, through its satellite communication equipment sends messages via an INMARSAT satellite. The satellite sends the messages to a ground earth station (GES) located at Eik, Norway. From the GES the signal is sent to the respective Air Traffic Control Centre (ATCC) via X25 data line, and will be shown as an ADS-blip in the controllers radar screen. Position messages get a "timetag" and are sent through a prioritized satellite channel. Other messages may be sent through a different satellite channel, depending on the urgency and the contract. One of the main benefits of M-ADS is full coverage down to sea level, e.g. in case of an emergency where the helicopter has to land at the sea.

The satellite communication part of the M-ADS system is absolute necessary to fulfill the Norwegian CAA's requirement to have coverage down to sea level. At the moment, the M-ADS have technical support until 2014. The availability of spare parts and new "boxes" is limited, the system is quite heavy (approx 19 kg) and rather expensive, both to install/retrofit and the communication costs are relatively high. There are some capacity shortcomings in the signal update rate and the system is not air-to-air (broadcast). A work group of The Committee for Helicopter Safety on the Norwegian Continental Shelf concludes that there should be looked for replacement systems for the future. The replacement systems should follow certified standards and be commercially available. In their recommendation Multilateration and ADS-B are mentioned. These systems do however not fill all the requirements based on coverage over the continental shelf and in the northern areas. To cover the whole coast of Norway from the Ekofisk field in the south to areas north of Norway it is estimated a requirement of 30 ADS-B ground stations. It seems like satellite coverage would be a necessity, especially for non-stationary installations. The work group suggests enhancing ADS-B with satellite communication, at least below a certain level.

Possible future areas of interest could be transmission via satellite of the helicopter technical status (Vibration Health Monitoring system VHM/HUMS) and Flight Data Recorder information. Other areas which have been discussed are satellite precision landings by helicopter at platforms.

PROPAGATION CHANNEL

There are two types of orbits that may be employed for a HEO satellite system; Tundra and Molniya. Both orbits have an inclination angle equal to 63.8°.

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 located over the same location on the earth surface. The apogee height is about 47 000 km. As a comparison, to the geostationary satellite height is about 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 about 39 000 km. Russia currently has several satellites in Molniya orbits, both for military applications and for television broadcasting.

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 $\mathbf{d} = \mathbf{r}_s - \mathbf{r}_a$ is the vector from the aircraft to the satellite. The vectors are given in Cartesian coordinates by (see Ref. [1]):

$$\mathbf{r}_a = R(\cos L \cos \theta_c \; \mathbf{i} + \cos L \sin \theta_c \; \mathbf{j} + \sin L \; \mathbf{k}), \quad (1)$$

$$\mathbf{r}_s = \frac{A \cos I}{1 + e \cos \theta_e} \cos \theta_e \; \mathbf{i} + \frac{A \sin \theta_e}{1 + e \cos \theta_e} \mathbf{j} - \frac{A \sin I}{1 + e \cos \theta_e} \cos \theta_e \; \mathbf{k}, \quad (2)$$

where R is the earth radius, h is the altitude of the aircraft, the angle L is the latitude of the aircraft, 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 $\mathbf{r}_a$:

$$\varepsilon = \frac{\pi}{2} - \arccos\left(\frac{\mathbf{d} \cdot \mathbf{r}_a}{|\mathbf{d}||\mathbf{r}_a|}\right). \quad (3)$$

The elevation angle for a Tundra satellite and a Molniya satellite as function of the latitude of the receiver is shown in Fig. 2 and Fig. 3. 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:

$$L_f = 20\log_{10}(d) + 20\log_{10}(f_c) + 92.44, \quad (4)$$

where d is the distance between the transmitter and the 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 Fig. 4

and Fig. 5, respectively. 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.

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

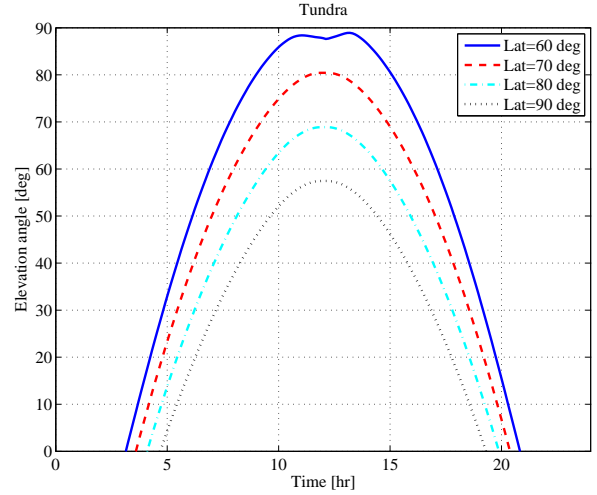$$f_d = -\frac{v_d}{c} f_c. \quad (5)$$

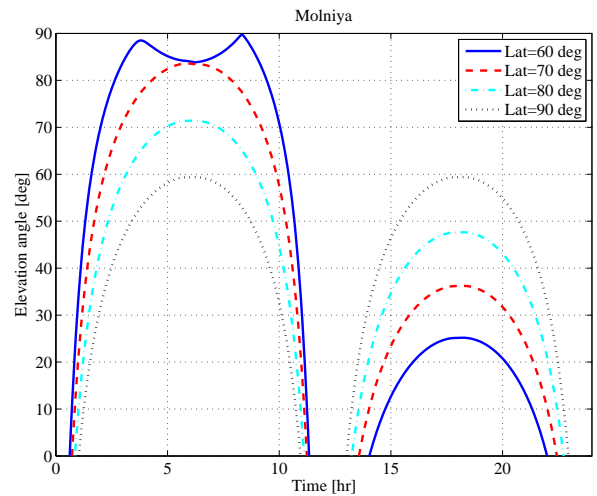**Figure 2 Elevation angle for Tundra satellites.**

Figure 3 Elevation angle for Tundra satellites.

The radial speed can be calculated using projection:

$$v_d = \mathbf{v} \cdot \frac{\mathbf{d}}{|\mathbf{d}|} = \left(\frac{d\mathbf{r_e}}{dt} - \frac{d\mathbf{r_c}}{dt} \right) \cdot \frac{\mathbf{d}}{|\mathbf{d}|}. \qquad (6)$$

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.
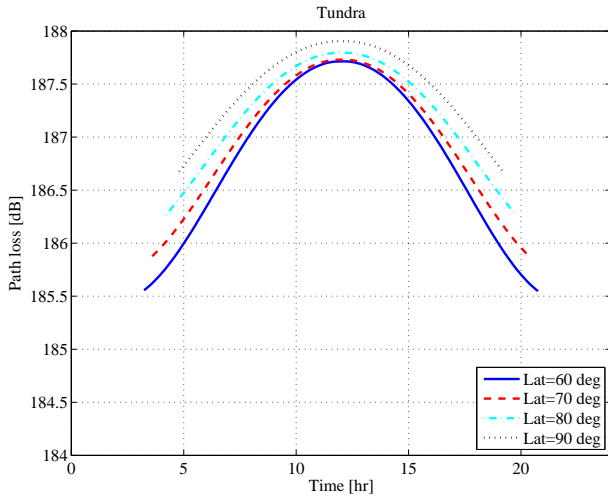

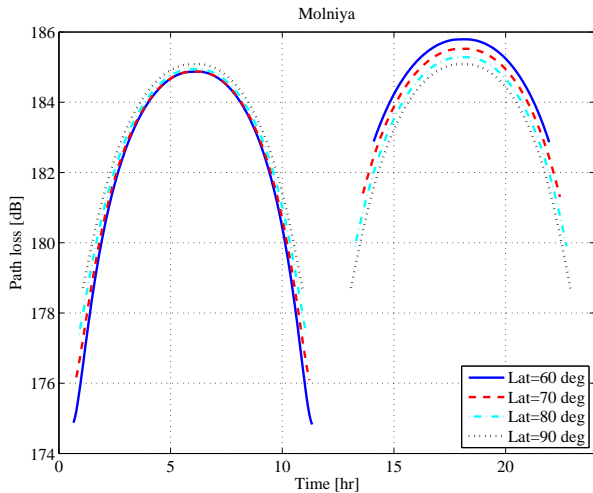**Figure 4 Free space path loss (Tundra satellites).**

Figure 5 Free space path loss (Molniya satellites)

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 it 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. 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.
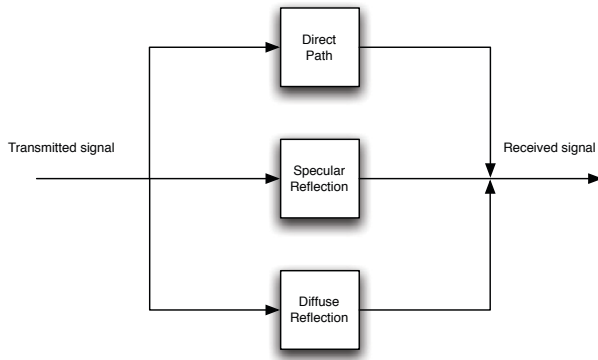
Multipath propagation due to reflections

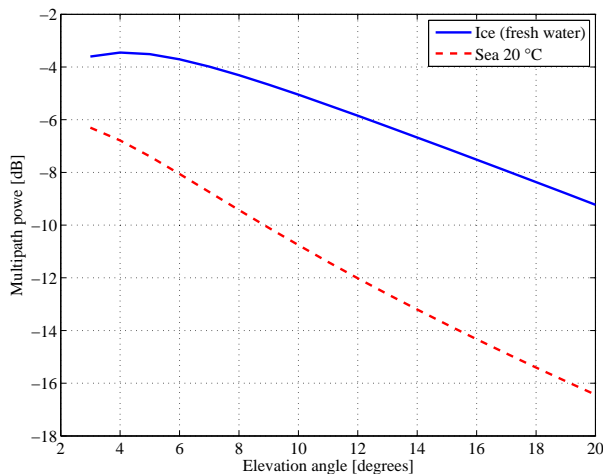**Figure 6 Aeronautical channel model**.

Figure 7 Signal power for ground reflections

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 Ref. [2], 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-racing 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 Fig. 6. 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 Fig. 7. As a consequence, communication over the icy polar cap will be more affected by multipath propagation than communications further to the south.

CONCLUSIONS

In this publication, different user groups depending on ATM services in the high north are described. The air traffic, and the diversity of it, will only increase in the coming years due to increased activity within oil production, increased sea traffic due to reduction of the ice cap, and less restriction on the transcontinental cross polar air traffic and also continental/local air traffic as the different airspace authorities become more coordinated. Due to the vast areas and lack of ground infrastructure, these users will depend on satellite based communication systems. A HEO

satellite constellation is in this respect a realistic alternative. The background for the work presented in this publication is therefore the interest and need to design a satellite communication system providing the same level of ATM security over northern and polar areas as over areas further to the south.

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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[1] Vilar J., J. Austin, 1991, Analysis and correlation techniques of Doppler shift for non-geostationary communication satellites, International Journal of Satellite Communications', Vol. 9, pp. 123-126.

[2] Steingass, A., A. Lehner.; F. Perez-Fontan F. E. Kubista, M.J. Martin, B. Arbesser-Rastburg, 2004, A high resolution model for the aeronautical multipath navigation channel, Position Location and Navigation Symposium (PLANS) 2004, pp. 357-365.

2009 ICNS Conference
13-15 May 2009