An Advanced Propagation Tool for Satellite ATM and Aeronautical Communications

J. Lemorton[1], J. Israel[1], T. Jost[2], M. Walter[2], A. Graziani[3], D. Vanhoenacker-Janvier[3], N. Floury[4]
[1] ONERA - The French Aerospace Lab, Electromagnetism and Radar Department, Toulouse, France (Joel.Lemorton@onera.fr)
[2] DLR - German Aerospace Center, Institute of Communications and Navigation, Oberpfaffenhofen, Germany
[3] UCL - Université catholique de Louvain, Louvain-la-Neuve, Belgium
[4] ESA - European Space Agency, ESTEC, Noordwijk, The Netherlands

***Abstract*— The objective of this paper is to present the development of a new software tool for the analysis of propagation effects on satellite-to-aircraft communications, valid for frequencies between VHF and Ka-band, and which takes into account the following technical/scientific issues:**

- **modifications induced on the aircraft antenna pattern by its installation on the platform (due to interaction with the structural elements of the platform) and corresponding short delay additional multipaths, including in the case of moving elements (e.g. helicopter blades),**
- **geometry of the trajectory and aircraft dynamics during movements including attitude,**
- **surface scattering effects for sea and ground surfaces, including vegetation layers,**
- **atmospheric effects due to troposphere at different altitudes and ionosphere.**

***Index Terms*— propagation, aeronautical communications.**

I. Introduction

The use of satellites for passenger and/or aircraft communications, including Air Traffic Management (ATM) has been considered already since the 1960's at VHF frequencies and since 1970's in L-band. At L-band, several concepts have been studied such as AvSat; existing satellites have been adapted for aeronautical communications, like Inmarsat originally with Inmarsat-2 and more recently with SwiftBroadband, and Iridium system; dedicated satellite payloads have also been deployed like MTSAT Aeronautical communications function. At Ku-band, the most important developments have been the NASA's Aero/Mobile Satellite Communications Testbed and the commercial system for high speed broadband Connexion by Boeing. At Ka-band, the Abate concept was proposed for interactive mobile multimedia services; experiments were performed in Japan with COMETS satellite and NASA's ACTS satellite. More recently, the Iris Program targets a new system for air-ground safety communications based on satellite in L-band for future European ATM Systems.

The design, development and verification of any communications system require reliable propagation channel models. Fixed satellite communication systems often rely on long-term statistical models, but aeronautical mobile satellite communications instead, need to consider channel models addressing a combination of propagation effects in any location and period and also considering dynamics of aircraft, satellite and environment (atmosphere, sea waves …). An aeronautical channel model for satellite communications needs to consider two main contributions (Fig. 1):

- a strong line of sight (LOS) component that is present all the time (except during maneuvers where the satellite signal might be blocked by the aircraft body) affected by ionospheric and tropospheric effects, and possibly by specular and/or diffuse scattering from the aircraft;
- a surface (ground, sea, ice, snow) scattering component which arrive with a certain delay, phase and attenuated power with respect to the LOS component.

The overall channel is considered time-varying due to various conditions: atmospheric dynamics, geometry changes due to aircraft flight (affecting not only the LOS, but also the fuselage scattering at each instant), dynamics of elements on the fuselage (e.g. blades for helicopters), time-variation of the surface scattering, and dynamics of the surface (e.g. sea waves). The effects of antenna pattern must not be neglected, the type of antenna may mitigate ground and fuselage multipath effects, but in cases such as banking maneuvers, multipath may arrive as strong contribution impacting the communications signal.

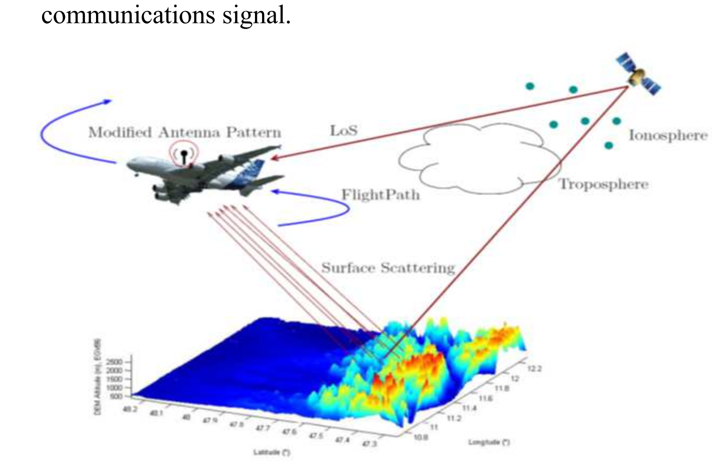

Fig. 1. The aeronautical propagation channel

Deterministic models allow to simulate any configuration in various geometries, frequency bands, surface types and phases of flight, whereas statistical models are simple to implement, but with a limited validity range.

A general satellite-to-aircraft channel model was presented by Bello in [1]. For sea reflections, the model included in ITU-R Rec. P.680 [2] is based on a model [3], which relies on Kirchhoff approximation of rough surface scattering for the diffuse reflective power. This approach is used in the aeronautical channel model for Inmarsat BGAN [4] and also adopted in ITU-R Rec. P.682 [5]. Other simple model based on multiple scatterers specular point theory [6] is often used for the modelling of rough sea surface reflection. ITU-R Rec. P.682 [5] also presents a model for landing approaches over ground with main application on satellite navigation. The model characterizes the fuselage contribution statistically depending on direction, and it is based on [6] and [8] with a stochastic state-based ground reflection model valid for land surfaces.

The fuselage contribution has been further studied from electromagnetic simulations [9]. In terms of physical modelling, a ray-tracing model for the satellite-to-aircraft channel was proposed in [10].

For the satellite-to-helicopter channel, few experimental results are reported, most of them at L-band. A periodic fading channel model for GPS propagation is observed depending on elevation and azimuth in [11]. Further analyses on the effects of rotors on GPS signal are discussed in [12].

Earth-space propagation models for atmospheric effects are described in ITU-R recommendations [13], [14] and [15]. For turbulence (tropospheric and ionospheric scintillations), more advanced simulation methods are addressed in [16].

So the objective of this activity was to develop a new software tool for propagation analysis of satellite to aeronautical communications, including more physically based models, valid from VHF to Ka-bands, and which could take into account the following technical issues:

- modifications induced on the antenna pattern by its installation on the platform,
- geometry of the trajectory and platform dynamics during movements including the attitude,
- surface scattering effects for sea and ground surfaces, including vegetation layers,
- atmospheric effects due to troposphere at different altitudes and ionosphere.

II. ANTENNA ISSUES

Issues related to the installed antenna on the aircraft platform are of three kinds:

- modifications of the antenna pattern in some directions (due to masking effects, reflected or diffracted waves, creeping waves …): this is mainly a narrowband effect which impacts the link budget. A modified antenna pattern has to be used taking into account the position of the antenna and the geometry of the platform.
- additional multipaths on the platform : this is a wideband effect modifying the channel impulse response (CIR).
- specific case of helicopter platforms : additional modulation of the antenna pattern and additional multipaths are caused by the passing of the blades around the antenna. This is both a narrowband and wideband effect. Performance of navigation and communication systems mounted on a rotorcraft is affected by the rotor: periodic blockage and in situ antenna response varying with frequency and time (delay and Doppler effects).

In this activity, it was decided to use external ElectroMagnetic (EM) numerical tools for calculating these effects for different antennas installed on various platforms, and to include the outputs of these calculations in the channel model simulator.

The use of an EM solver depends at first order on the ratio “size of the platform” to the wavelength, for computer time and memory requirement issues, and is also related to the complexity of the Computer Aided Design (CAD) model of the platform. The performances of EM solvers depend on the type of computer (standard PC, supercomputer) and the efficiency of the EM algorithms among exact methods or asymptotic ones. The main drawback of exact methods is that the domain of application is limited because the large computational resources required. For specific aircraft shape and dimensions, the available computer resources determine the upper frequency limit to solve the EM problem in reasonable computational time. At higher frequencies, when the electrical size of the aircraft becomes too big, exact methods become unpractical and the so-called asymptotic methods have to be used.

From the review performed in this activity, for antenna pattern calculation, MoM (Method of Moments) and its improved implementation MLFMM (Multi Level Fast Multipole Method) were considered as the most precise methods for evaluating the modifications brought to the isolated antenna pattern by the installation on board a platform. However MoM and MLFMM are frequency based techniques and cannot give channel impulse response in the time domain.

So, based on our experience, in order that the simulation is manageable in time and memory for a large platform, even on a high performance PC, it was assumed that:

- MoM alone can be used up to several hundreds of MHz on the larger airborne platforms, and one GHz on the smaller platforms. MLFMM is very efficient for decreasing the number of unknowns and enabling larger platforms to be considered. With MLFMM, a large platform can be dealt with even at several GHz.
- Asymptotic techniques can be used above some hundreds of MHz on most platforms, and are even better for higher frequencies. The validity of asymptotic algorithms depends on the size of smaller details of the CAD model which have to be higher than three or four wavelengths.

For propagation channel estimation, only the main contributions may have to be taken into account precisely, enabling some constraints to be relaxed. On large scenes or objects, asymptotic approaches are the most realistic and efficient ones to use and are the only methods that permit a large diversity of outputs, e.g. angle of arrival, Doppler analysis or power delay profile, for parametric studies.

In our activity, it was decided to use the general asymptotic tool SE RAY EM – FERMAT developed by ONERA and the French company OKTAL-SE (www.oktal-se.fr), with a dedicated application SE DIAG for antenna pattern and CIR calculation.

III. Dynamics of the Platform

Modelling the dynamics of a platform is in general a complex field of research. All formulations are based on the general equations of motion which are modelling the motion of a rigid body. In this activity, we had mainly to consider aeronautical platforms for Earth-space aeronautical communications. However we added also ship platforms to be able to assess Earth-space maritime communications.

A. Aeronautical Dynamic Model Simulator

In order to simulate the motion of an aircraft, we used the open-source program JSBSim [17] to simulate the dynamics. JSBSim is used in flight simulators like FlightGear [18] to simulate the dynamic behavior of the aircraft. JSBSim is an open source flight dynamics model programmed in C++. It supports a various set of aircraft and engine models which have been derived from textbooks and available technical reports. Autopilot simulation including landing is possible but limited to certain aircraft. JSBSim itself runs only in batch mode using XML files as input and text files as output. The program can be downloaded from [17].

JSBSim tries to simulate the aircraft dynamics as realistic as possible. Therefore, the behaviour of the aeronautical platform follows a realistic flight-path with the inertia of the rigid body. Hence, some knowledge on aerodynamics for using JSBSim is required as otherwise, literally speaking, the aircraft crashes into the ground. It should be clear that aircraft have a maximum altitude for operation or cannot change the direction immediately for example.

For the wave propagation channel simulator, JSBSim is used to simulate the aircraft in autopilot mode performing fly by maneuvers at waypoints given by the user. Therefore, the user needs supply only a limited set of coordinates for the trajectory while JSBSim simulates the aircraft attitude and flight route.

B. Ship Dynamic Model

As no full data set for a ship in terms of hydrodynamic coefficients could be found in literature, a simpler way to model the ship dynamics was chosen from [19]. The method described in [19] is based on a close-form description of the ship roll, heave, and pitch motion by an individual mechanical filter in frequency domain. The filters take the motion of the ship and the wave spectrum of the sea into account but not the ocean current, wind or thrust forces. Additionally, it is assumed that the motions for pitch, roll and heave are independent to each other.

IV. Surface Scattering Issues

Ground scattering may be responsible for significant multipaths which affect the aeronautical channel. The field of surface scattering is a research area since a very long time. Because of the computational complexity for solving the Stratton-Chu integral directly, many different simplifications have been derived as the Kirchhoff approximations or the IEM (Integral Equation Model) for example. All these methods are valid only within certain validity regions which depend on the frequency, roughness, and the surface correlation length. Even if a method is used within its validity region, it should be understood that additional approximations need to be done such as the form of the surface correlation function or the value of the electromagnetic parameters. In terms of the surface correlation function normally a Gaussian function is used because of its simplicity. In terms of electromagnetic characterization, many different parameters are needed for a single frequency. Therefore, to avoid these difficulties, the state of the art aeronautical channel models are mainly based on simplifications. The models in [1] and [20] assume Kirchhoff approximations for higher frequencies and a flat Earth sea scattering. The ITU recommendation [5] models the Earth scattering by a reflection whose power comes from flight measurements near Graz airport.

In our activity, the basis of the surface scattering multipath calculation has been reused from the previous PHYSTAT study [21][22]. The main changes are the use of IIEM (Improved Integral Equation Model) from [23] as ground scattering model and the addition of a possible vegetation layer above the ground. New datasets at a global scale are used for describing ground permittivity (soil data from Harmonized World Soil Database: http://webarchive.iiasa.ac.at) and roughness (from AMSR-E passive microwave remote sensing [24]), and the presence of vegetation (ESA Globcover image: http://due.esrin.esa.int).

The terrain scattering is calculated by point scatterers distributed on the ground with a defined power and angular pattern [21]. To calculate the pattern and the power for each scatterer, physical rough surface scattering (now IIEM) is applied using digital elevation data to consider topography. Within the channel model point scatterers are distributed around the specular point reproducing the specular reflection itself and diffuse scattering around this point.

V. Atmospheric Effects

The purpose was the implementation of atmospheric models to account for the effects of the atmospheric transmission media: troposphere and ionosphere. The models were mostly based on the ITU-R recommendations; a detailed view of the tool is in [25].

The troposphere has been modelled considering different attenuation contributions: clouds, rain, scintillation, water vapour and oxygen.

The ionosphere has been modelled considering (1) Ionospheric delay, different concentration of electrons cause variations in the refractive index which change the path of the RF signal. This is mainly to be considered for navigation signals. (2) Ionospheric scintillation, when a RF signal traverses a region of small scale irregularities in electron density, fluctuations might occur and cause loss of lock.

The main improvement with regards to existing models [13] [15] consists in taking into account the platform altitude for tropospheric effects. Since the platform can be in the cloud or rain layers, only part of the total attenuation should be taken into consideration associated to the corresponding integrated water vapour and liquid water contents.

Time series are generated for representing these effects on the propagation channel considering smooth transitions with altitude during a specific scenario. As proposed in [15], the time series are based on white Gaussian noise (WGN) generators and tuned with local attenuation parameters. In order to prevent long time series to be generated without any significant effects, the simulator includes the possibility to force the presence of rain.

VI. Validation and Case Studies

All the elementary models integrated in the software tool have been first validated as compared to published results. Some of them were already recommended by ITU or had been evaluated in other frameworks.

Below we show examples of Case Studies performed with the new software tool. It must be mentioned that the simulator is able to take into account physical phenomena (related to the propagation channel) that have very different time scales (for example rain attenuation and blade masking) and requires very different time sampling. Therefore, for the exploitation of the tool for communication link design, the user should take care of setting realistic input parameters from the physical and the computational point of view (time sampling coherent with the time scale of the physical phenomenon to assess).

A. Long haul aircraft in the approach phase

This example tries to highlight the sea scattering effects producing multipath components on the propagation channel between a low elevation satellite (5°) and a large aircraft in the approach phase of an airport, depending on the frequency band (VHF, L-band or Ka-band) and the type of antenna on-board (hemispherical or directive). The trajectory is a straight line, slope 3°, path length 20 km, with starting altitude at 10 km and final altitude at 300 m.

It can be seen in Fig. 2 that ground multipath components cause the total power to slightly vary. Fading effects are not too deep since the antennas are pointing upward. This is even more the case with directive antennas (L-band and Ka-band). At Ka-band, as expected, it can be seen that tropospheric attenuation increases as the altitude decreases.

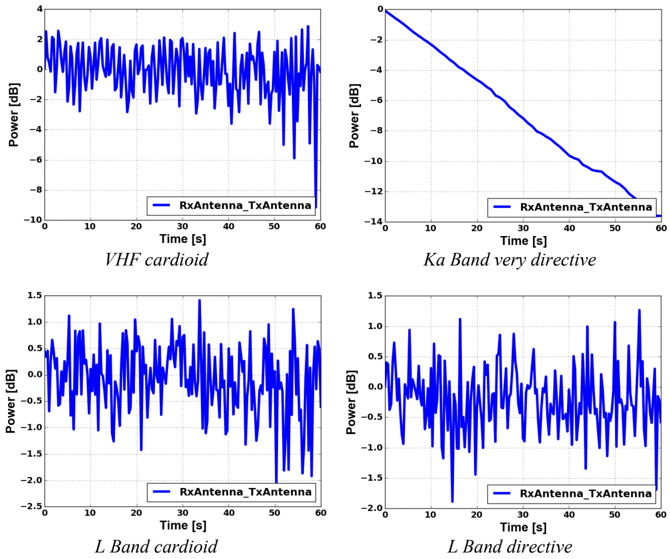

Fig. 2. Copolar power time series (with atmospheric attenuation, with normalization to LOS, without aircraft)

B. Blade effects for helicopter in stationary flight

This example tries to highlight the effects of the blades of a helicopter on the propagation channel between a satellite at moderate elevation (30°) and a helicopter in stationary flight above the ground surface. Diversity technique is also investigated with two antennas spatially separated by more than the blade width.

Generally speaking for this case, the ground multipath power is very weak due to the elevation of the satellite and the antenna patterns (Fig. 3). For separate antennas, the multipath components are not entirely correlated. This is the reason why the channel is not exactly the same at each point. The general behavior is on the contrary similar. Note that at Ka-band with the directive antenna, the diversity scheme is useless since no multipath component reaches the receiver, being filtered by the antenna pattern.

When the structure of the helicopter is taken into account, and especially the blades, we can see in Fig. 3 that the passage of the blades masks the line of sight. The effect is reinforced for directive antennas and high frequency where a deep masking is obtained. For the cardioid antenna at L-band, there is some scattering effect on the blades that creates some interference with the LOS component.

The blade effects are normally not entirely simultaneous on the two antennas, separated by a distance higher than the blades width. Therefore, there should be some kind of time diversity provided by the position diversity. In order to notice the effect, the time sampling for the simulation must be sufficiently short.

In Fig. 4 is shown the wideband capability of the tool which calculates all components in amplitude, phase and delay from which can be extracted the Doppler characteristics of the channel, here at L-band. The Doppler spread is low (20 Hz) if the blades are not considered whereas as expected it increases up to 2 kHz with the blades.

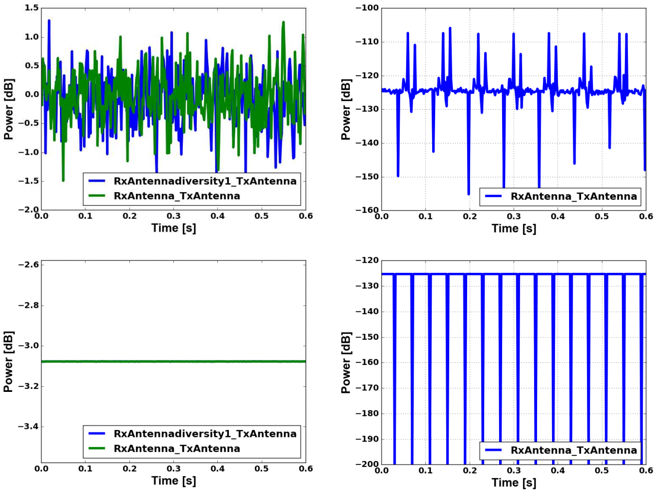

Fig. 3. Copolar power time series with (top) L-band cardiod or (bottom) Ka-band directive antenna : (left) with normalization to LOS, without helicopter (right) without normalization to LOS, with blade effects

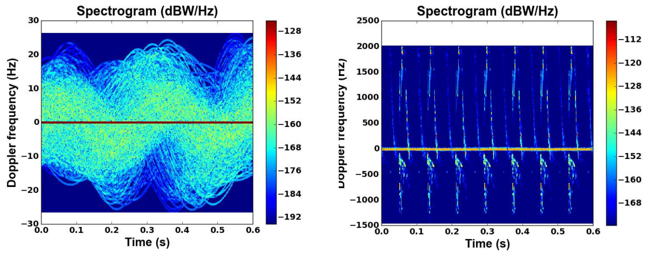

Fig. 4. Spectrogram (left) without and (right) with EC225 blades

VII. Conclusions

Apart from scientific work devoted to the selection of the best models to take into account the above mentioned effects, the main output of the activity is the Advanced Propagation Tool for satellite ATM & aeronautical communications. This simulator has been assessed through a large set of validation cases and used in specific case studies in order to show its potentialities for communication link performances assessment. Further activity is foreseen, especially for in-depth comparison with flight measurements.

Acknowledgment

This work has been carried out in the framework of ESA contract ESTEC 4000110588/14/NL/LvH "Advanced Propagation Tool for Satellite ATM and Aeronautical Communications". The authors would like to thank ESA for its support (and ESA GlobCover 2009 Project), as well as Dr. C. Pereira, former colleague at Université Catholique de Louvain, for its preliminary activities in the project.

References

[1] P.A. Bello, "Aeronautical channel characterization," IEEE Trans. Commun., vol. COM-21, pp. 548-563, May 1973.

[2] ITU-R P.680-3, "Propagation data required for the design of Earth-space maritime mobile telecommunication systems", 1999.

[3] Y. Karasawa and T. Shiokawa, "A simple prediction method for L-band multipath fading in rough sea conditions," IEEE Trans. on Communications, Vol. 36, No. 10, pp. 1098-1104, October 1988.

[4] A. Jahn, M. Richharia, M. Alvarez, P. Fines, N. Kaluvala, "Aeronautical channel model for broadband L-Band satellite communications", Proc. 23rd Comm. Satellite Sys. Conf, Sept. 2005.

[5] ITU-R P.682-3 "Propagation data required for the design of Earth-space aeronautical mobile telecommunication systems", 02/2012.

[6] D.E. Barrick, "Rough surface scattering based on the specular point theory," IEEE Trans. Antennas Propagation, vol. AP-16, July 1968.

[7] A. Lehner, "Multipath channel modelling for satellite navigation systems", PhD Thesis, 2007.

[8] A. Steingass, A. Lehner, F.Pérez-Fontán, E. Kubista, B. Arbesser-Rastburg, "Characterization of the aeronautical satellite navigation channel through high-resolution measurement and physical optics simulation", International Journal of Satellite Communications and Networking (26) , pp. 1-30, 2008.

[9] L. Lozano et al. "Electromagnetic simulations for aeronautical satellite communications channel mode", EuCAP 2012, Prague

[10] K. Lai, M. Cherniakov, "Ray-tracing model of satellite to aircraft communication in aeronautical satellite communication system," TENCON 99. Proc of the IEEE Region 10 Conf. , vol.1, 1999.

[11] M.P. Lavenant et al. "Digital Communications for the Satellite to Helicopter Channel", 11th National Space Engineering Symposium, Sydney, 1997.

[12] G. Brodin, J. Cooper, D. Walsh, J. Stevens, "The effect of helicopter rotors on GPS signal reception," Journal of Navigation, 58 , pp 433-450, 2005.

[13] ITU-R P.618-12, "Propagation data and prediction required for the design of Earth-space telecommunication systems", 07/2015.

[14] ITU-R P.531-11, "Ionospheric propagation data and prediction methods required for the design of satellite services and systems", 02/2012.

[15] ITU-R P.1853-1, "Tropospheric attenuation time series synthesis", 02/2012.

[16] V. Fabbro, N. Jeannin, K. Djafri, Y. Béniguel, T. Deloues, D. Vanhoenacker-Janvier, J. Lemorton , A Propagation Toolbox for Advanced Modelling of Coherent Propagation Effects on Active Microwave Remote Sensing , IGARSS 2012

[17] JSBSim, "An open source, platform-independent, flight dynamics model in C++" Online, 2015. http://jsbsim.sourceforge.net.

[18] FlightGear, "FlightGear Flight Simulator" Online, 2015. http://www.flightgear.org/.

[19] J.J. Jensen, A.E. Mansour and A.S. Olsen "Estimation of ship motions using closed-form expressions" Ocean Engineering, 31(1):61--85, 2004.

[20] M. Richharia, N. Kaluvala, P. Fines, M. Álvarez-Daz, and A. Jahn. "Aeronautical Channel Model for Broadband L-Band Satellite Communication," Rome, Italy, September 25-28 2005.

[21] J. Lemorton, J. Israel, M. Ait-Ighil, G. Carrie, C. Oestges, T. Jost, F. Perez-Fontan, "Physical-Statistical Models For Mobile Satellite Communication Systems below 10 GHz" Final Report ESA/ESTEC 4000104006/11/NL/AD, document ONERA RT10/19147, Dec. 2013

[22] J. Lemorton, J. Israel, M. Ait-Ighil, G. Carrie, C. Oestges, T. Jost, F. Perez-Fontan, "Physical-Statistical Models For Mobile Satellite Communication Systems below 10 GHz" URSI Commission F Triennial Symposium, Ottawa, Canada, May 2013

[23] A.K. Fung & al, "An improved IEM Model for bistatic scattering from rough surfaces", Journal of Electromagnetic Waves and Applications, Volume 16, Issue 5, 2002

[24] X.Z. Chen, ,Y. Li, Y.X. Su, L.S. Han, J.S. Liao, S.B. Yang, "Mapping global surface roughness using AMSR-E passive microwave remote sensing" Geoderma 235–236 (2014) 308–315

[25] A. Graziani, D. Vanhoenacker-Janvier, C. Pereira, C. Riva, A. Vergani, J. Lemorton, "Synthetized tropospheric total attenuation time series for satellite-to-aeronautical link from L to Q band", 10th EuCAP, April 2016