OPTICAL-SDMA FOR BROADBAND AERONAUTICAL COMMUNICATION

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ABSTRACT

Broadband communication for aircraft passengers is facing one of the most promising markets of near future. While currently systems introduced in L and Ku band are already limited in bandwidth considering service provisioning to several airline fleets, this paper will adopt optical free space communications for aeronautical communication. Based on general design and network issues, a proof of concept for different optical aeronautical satellite terminals is given. Beam separation and technological implementation examples are provided and compared to today's microwave implementations. Link budget calculations taking atmospheric propagation into account are concluding the overall system concept.

INTRODUCTION

Aircraft communication is and will continue to be one of the most promising markets where satellite services are indispensable, due to the stringent requirement of global coverage. Outdated communication systems for Air Traffic Management (ATM) and the demand of offering a terrestrial like communication environment to aircraft passengers and crews, call for systems with increased capacity and bandwidth, in order to make airtravelling more productive more pleasant, and more secure.

The typical classification of aeronautical communication services in Cockpit and Cabin Services, shows in a more detailed view, that service classes differ significantly in bandwidth, security, integrity, quality of service and operational requirements. Cockpit Services like Air Traffic Services (ATS) or Airline Operational Control (AOC) will also in future be more or less narrowband. In contrast Cabin Services, especially Airline Passenger Correspondence (APC), requires broadband communication systems, but less system integrity and availability as for instance ATS.

Current trends and recently revealed plans of the global players in the field, clearly anticipate a combined navigation and narrowband communication satellite constellation for new Air Traffic Management (ATM) as well as an evolutionary approach building upon existing GEO systems and a shift to higher frequency bands for broadband aeronautical communication [1].

However, as the envisaged satellite systems have not been strictly designed for broadband aeronautical communications, such approaches show several deficiencies and limitations. A not 'truly' global coverage as not covering polar regions and capacity limitations to a few hundred kbps transmission rates per aircraft combined with an enormous technological effort for the aircraft terminal and especially antennas are the most obvious drawbacks.

One key issue for the success of aeronautical communication, besides the support of a terrestrial like communication environment in the aircraft for user acceptance [2], is a lightweight, small, and power saving aeronautical terminal with low aerodynamic drag to ensure an economic implementation with minimal loss of aircraft payload and flight range. Taking the classical advantages of optical freespace communications - smallest beamwidth at minimal terminal size - this paper will show that optical communication is well suited for aeronautical applications, by optical aircraft to satellite links (O-ASL), implementing Space Division Multiple Access (O-SDMA) with an optical terminal at the satellite (sat-OT).

NETWORK CONCEPT

The minimum elevation angle is one of the key parameters for satellite system design. It is usually a parameter of earth-space geometry and related to terminal or user positions on earth only, but not to terminal or antenna orientation.

The (nominal service) coverage area or footprint of a satellite is defined as the area containing all locations on earth from which the satellite is seen with an elevation angle larger than the minimum elevation against the horizon.

With the aircraft being an agile attitude changing vehicle, however, it is important to consider relative elevation angles with respect to the virtual horizon of the aircraft, which is the plane defined by the roll and pitch axes of the aircraft body.

Assuming a standard roll manoeuvre angles of 25° and an optical aircraft terminal (aero-OT) top mounted on the aircraft's fuselage with a steering range or angle of view of 0° to 90° in elevation and 360° in azimuth, and thus hemispherical sight capability, the relative minimum elevation angle of the satellite system is translating to 25° (see Figure 1).

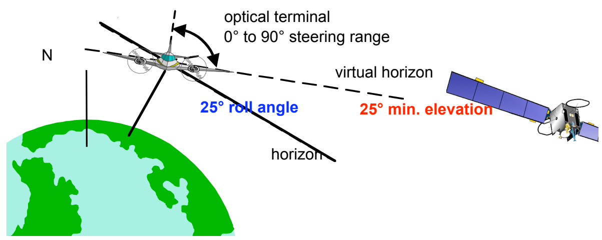


Fig. 1 : Relative Minimum Elevation Angle.

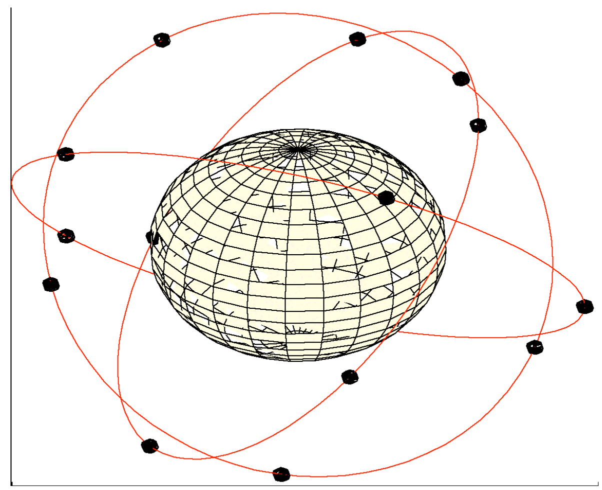
Investigations of relevant characteristics of an aircraft's rigid body geometry, inspired by its inherent impact on effective line-of-sight view conditions from a point on the fuselage surface, where a potential antenna may be mounted [3], have shown that aeronautical terminals at top of fuselage are suffering form tail structure shadowing. This shadowing event is only influenced by the pitch angles of the aircraft, which are by far lower than the roll angles. Together with an installation above the wings or even more shifted to the cockpit the minimal elevation provided by the satellite system guarantees continuous line of sight conditions for the optical link.

Implementation of satellite antennas at Airbus and Boeing show at the moment, that construction issues prevail all theoretical analyses, but perhaps with smaller antennas at optical frequencies the placement options increase again. An even more optimised installation at the top of the tail structure might be applicable with the minimised sized of an OAT, also allowing negative elevation angles during roll manoeuvres. Following such an installation and angular agility range of the OAT coverage can be reached even for polar near flight routes with a GEO satellite system .

<u>Reference Satellite Constellation: MEONET</u>

According to the systematic system design of an AirCom satellite communications system in [2], the investigations will be based on a reference constellation called MEONET which provides truly global coverage at a minimum elevation angle of 25°. Being a Walker delta constellation, it has been chosen for study purposes here as it also provides appealing multiple coverage statistics at mid latitudes, and for its potential to have a convenient intersatellite link topology added in a future step of advanced constellation design.

Fig. 2 displays the MEONET constellation and summarises the relevant constellation parameters, and Fig. 3 illustrates the size of the coverage area of one MEONET satellite for 25° elevation, as well as its potential intersatellite connections to neighbouring satellites.



Orbit type	Walker	No. of satellites	15
Orbit altitude	10390 km	No. of orbits	3
Orbit period	5 h 59 min	Inclination	54°

Fig. 2: MEONET constellation.

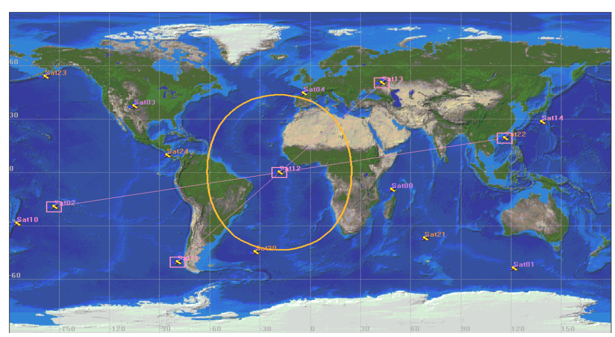


Fig. 3: Footprint of a MEONET satellite.

<u>Network dimensioning: Number of Planes per Satellite</u>

For later investigations one of the key parameters defining the optical satellite terminal is the worst case number of planes inside one satellite footprint.

These and other relevant network dimensioning parameters are derived from a database of world-wide scheduled flights including origin/destination, departure/arrival times, single-/multihop routes, additional route information, route classification, aircraft type and lead to a classified distribution of aircrafts over location and time per satellite footprint and of 'optical' spotbeams, defined later on.

Focussing further on the highly interesting North Atlantic flight market, two key results can be derived processing these data with the dynamic constellation overlaid. Firstly, a key design parameter for the optical satellite terminal is the maximum number of aircrafts covered by one satellite at any time. Depending on the actual satellite selection criterion in the case of multiple coverage, this number is in the order of 200 to 300 for the North Atlantic flights.

Secondly, for further studies it is also indicative to have a fairly good impression of the typical distribution of aircrafts within the footprints. A first impression for that is given in the snapshot in Fig. 4.

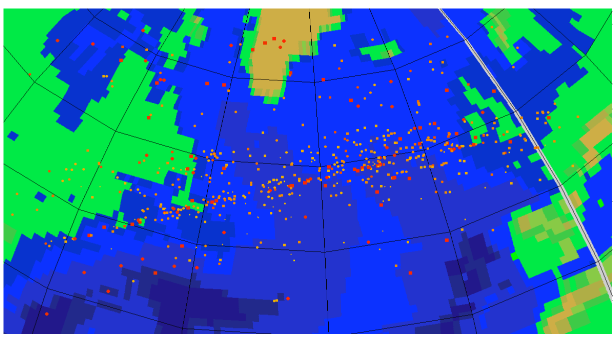


Fig. 4 : Snapshot of the North Atlantic flights.

<u>Atmospheric Restrictions on Optical Links:</u>
Optical transmission through the atmosphere is influenced by different types of attenuation, blocking by cloud-coverage, and atmospheric index-of-refraction turbulence (IRT). It is well known that weather impact (and likewise cloud coverage) is limited to the troposphere, making cloud occurrence of significant thickness *above* the typical cruise-altitude of commercial airliners very unlikely. Due to the reduced air-thickness at these altitudes also attenuation by atmospheric molecules (rayleigh-scattering, molecular absorption) becomes very small, especially when the transmission wavelengths are chosen to be outside of molecular absorption bands. A not negligible remaining attenuation effect comes from aerosol particles which tend to agglomerate in altitudes around 20km above see-level, especially volcanic activity increases their density. Existing measurements and databases allow the estimation of this effect not to exceed -2dB in an optical up/downlink scenario from aircraft cruise altitudes.

IRT in the aeronautical uplink channel causes beam-wander, beam-spreading, wavefront-distortion and further short-term effects on the optical field-distribution [6,8], these affect the link quality by fading. But these effects can be shown to be nearly negligible in our case of an *aeronautical* optical up- and down-link with a large transmitter divergence.

The impact of IRT also reduces with increasing wavelength, therefore we prefer here the well-established 1550nm technology which also offers a huge supply of existing components with Tx-powers up to 1W and a range of Tx-laser wavelengths from 1300nm to 1600nm. It furthermore allows to avoid wavelengths regions with atmospheric molecular absorption lines (see Fig. 5). The mentioned effects have been discussed more extensively in [6].

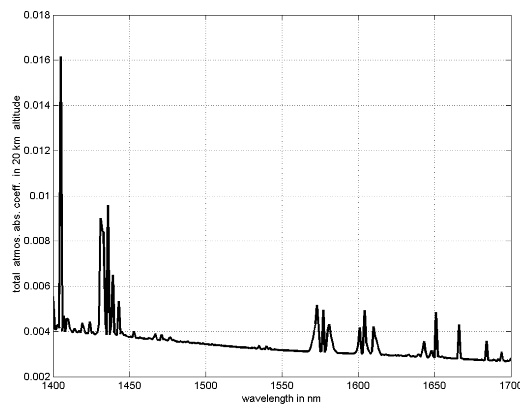


Fig. 5 : Total atmospheric absorption coefficient (in km^{-1} to basis *e*) at 20 km altitude with high volcanic activity level. Thin molecular absorption lines can clearly be distinguished from aerosol- and rayleigh-background.

<u>AERONAUTICAL TERMINAL</u>

Most important for aircraft communication equipment is an economic implementation with minimal loss of aircraft payload and flight range. Besides the terminal weight, also power consumption, size and minimal aeronautical drag are essential parameters of an aeronautical terminal.

Current aeronautical microwave antennas designs (e.g. for Ku or Ka band systems with a few hundred kbps transmission rate) have dimensions of up to one square meter antenna surface and several tens of centimetres in height [4][5].

Proof of concept:

Here we will develop the proof of concept for multiple aircraft to satellite laser communications with one approach based on existing technology [7] and a further approach with not yet available optical beamforming technology. Either concept can produce spotbeam like optical transmit and receive patterns of only a few hundred meters in diameter, further cited as optical spotbeams. Communications link budget calculations will lead to results for communication scenarios for different data rates and terminals. Investigations for optical links between High Altitude Platforms [6] have already shown that high data rate communications is feasible, at data rates up to several hundred Mbps, and optical transmit-power levels of less than 1W for several hundred km stratospheric path.

Transmission technology:

Transmission technologies with different sensitivities and levels of maturity exist for optical free space communications. Sensitivity is usually stated in photons per Bit (Ph/B), which for experimentally verified systems ranges from 20Ph/B (homodyne-BPSK at 1064nm with 622MBps) to approx. 1000Ph/B (Intensity-Modulation / Direct-Detection with standard 1550nm technology at 2.5GBps), each at a Bit-Error-Rate of 10^{-9}. We will here use a conservative and experimentally verified number of 300Ph/B for BER=10^{-4} which holds for datarates from approx. 10MBps to 500MBps [9]. This BER is comparable to that assessed also in microwave-uplink, additional channel-coding will allow to achieve net-BERs better than 10^{-9} [11].

Beam-Pointing of Aeronautical Terminal:

The possible link performance heavily depends on the beam-pointing accuracy and tracking ability of the optical terminals, this assignment is usually called Pointing, Acquisition, and Tracking (PAT). The typical achievable remaining pointing error of such aeronautical optical terminals can be reduced to a $\_{rms}$ around 20µrad assuming Gaussian error distribution.

Beam-Separation:

When using the same telescope optics for the Tx- and Rx-beam in the aeronautical terminal (as assumed here) it is crucial to avoid illumination of the Rx-detector by backscattered outgoing light. This can very effectively be done by using different wavelengths for the up- and downlink (e.g. 1550nm and 1625nm, see Fig. 5) and chromatically separating these with beamsplitter elements. Unlike with optical inter-satellite communications this asymmetric concept does not limit the overall system flexibility in our case.

SATELLITE AND OPTICAL-SDMA

This aeronautical, optical communication system will involve one spot beam per aircraft/user, steered actively towards the communication partners. There usually arises in communication systems the need to assign different physical channels to different users to avoid severe interference from co-channel users (leading to time, frequency or code division multiple access schemes).
The optical communication system described in this paper allows a very efficient exploitation of the *spatial* separability of the different user signals (both in uplink and downlink), because of the very small optical spotbeam size as compared to the minimum distance between two aircrafts.

Hence, according to the concept of space division multiple access (SDMA), the suppression of co-channel interference is guaranteed by the sufficient spatial separation of the users and there is no further need for assigning different physical channel (e.g. wavelengths or timeslots). A main advantage is a great simplification of the design of the optical TX and RX components at both the aircraft and the satellite as they operate at only a single wavelength. Further, as SDMA is usually suggested to increase the spectrum efficiency of a system, the narrow beamwidths realised here allow a reuse of the spectrum of 100% (or almost as indicated further below).

Classical optical laser communication requires a pair of transmitters/receivers for every communication link to be established [6,7]. Thus the number of required terminals per satellite would be, according to the network dimensioning analysis, the maximum number of aircrafts per satellite footprint. But at least the number of satellite Rx-terminals can be reduced by applying focal detector arrays as described subsequently.

Satellite Tx-Antenna-Array with Conventional Technology:

One Tx-telescope is used for each downlink to one aircraft. With the MEONET-Constellation covering a total footprint-diameter of approx. 10000km up to 64 links could be established with an antenna array as sketched in Fig. 6.

With a total area of only 0.64m^2 this kind of optical antenna-array already takes less volume than a typical Ka-Band antenna.

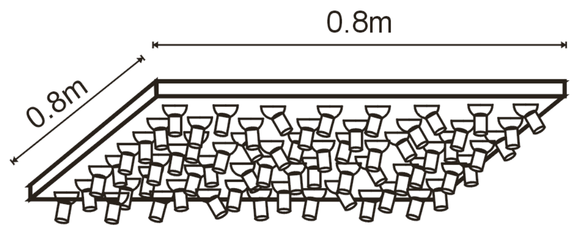


Fig. 6: Mechanically steered satellite Tx-antenna array; 64 (8x8) Tx-telescopes with ca. 90° pointing-range in each axis; each telescope having 3cm diameter resulting in a far-field on-axis gain of 98 dB at 1550nm wavelength.

Conventional Satellite-Rx-Antennas:

For the Uplink from aircraft to satellite with an aero-OT as described above a satellite Rx-antenna array as shown in Fig. 7 can be used.

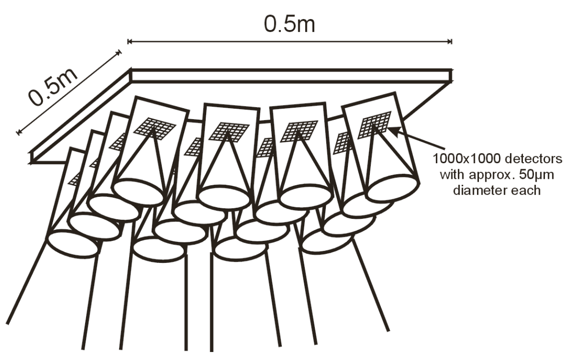


Fig. 7: Fixed satellite Rx-Antenna-Array for 40° Field-of-View, 16 (4x4) Rx-Telecopes with 10cm diameter each, 10° Field-of-View of each Telescope, with 1000x1000 focal detectors each, resulting in 0.01° (170µrad) resolution for the Uplink, equivalent to 1.8km (2.5km at edge-of-coverage) on-ground resolution with the MEONet-constellation

The resolution possible with this satellite-Rx-terminals would allow one dedicated uplink from an aircraft with at least 2.5km lateral spacing. For smaller aircraft-approaches the link would be blocked for a few seconds, or more sophisticated transmission techniques could reduce link-capacity, but keep up the link during this time. In contrast to the downlink Tx-antenna array, the Rx-antennas need no mechanical steering.

The necessity of several Rx-telescopes as shown here could (but not necessarily must) arise from optical focal spot quality reasons: The off-axis angle when using one Rx-telescope with up to 20° skewed incoming beam might cause too much aberration and thus focal spot blurring beyond an acceptable size. For other constellations where this angle is not too large (e.g. with a GEO-satellite) the uplink could also be performed by only one satellite Rx-terminal which then could also have a larger size. Handovers would occur between the different Rx-terminals which could of course be easily handled on one satellite bus.

Link-Budgets for Conventional Terminal Technology:

Uplink-Budget for the conventional optical SDMA-antennas:

With the proposed transmission scenarios the uplink performance can be assessed as follows (antenna-gains are based on derivations given in [10]):

aircraft-Tx-terminal:	3cm diameter	10cm diameter
Tx-power @ aircraft	+20 dBm	+20 dBm
Tx-terminal-losses	-1.5 dB	-1.5 dB
on-axis Tx-antenna-gain	+98 dB	+108 dB
atmos. IRT-losses	-2 dB	-2 dB
atmos.-attenuation losses	-2 dB	-2 dB
freespace loss (13000km)	-280 dB	-280 dB
Rx-antenna-gain (10cm)	+106 dB	+106 dB
PAT-losses	-1 dB	-2 dB
Rx-terminal-losses	-1 dB	-1 dB
detector-efficiency	-1 dB	-1 dB
Rx-power detected	-64.5 dBm (0.35nW)	-54.4 dBm (3.5nW)
maximum uplink-datarate:	9 MBps	90 MBps

The resulting maximum possible datarates are calculated for the receiver-sensitivity of 300Ph/B (with $1.3 \cdot 10^{-19}$ J/Ph at 1550nm) as mentioned above.

Downlink-Budget for the conventional optical SDMA-antennas:

The downlink-budget for the proposed configuration yields the following performance:

aircraft-Rx-terminal:	3cm	10cm
Tx-power @ satellite	+26 dBm	+26 dBm
Sat-Tx-terminal-losses	-1 dB	-1 dB
on-axis Tx-antenna-gain	+98 dB	+98 dB
freespace loss (13000km)	-280 dB	-280 dB
atmos.-attenuation losses	-2 dB	-2 dB
atmos. IRT-losses	-2 dB	-2 dB
Rx-antenna-gain	+96 dB	+106 dB
PAT-losses	-1 dB	-1 dB
Rx-terminal-losses	-1.5 dB	-1.5 dB
detector-efficiency	-1 dB	-1 dB
Rx-power detected	-68.5 dBm (0,14nW)	-58.5 dBm (1.4nW)
max. downlink-datarate:	3.6 MBps	36 MBps

Phased-Array OSDMA Approach:

The concepts shown in (Fig. 6 and 7) - though already featuring superior performance - obviously lack the elegant approach of several spot beams produced with only one antenna-aperture as known from microwave phased-array antennas. Also, it would be desirable to achieve higher datarates in the downlink than in the uplink as this would better match the anticipated service requirements.

New optical transmitter and receiver concepts for the satellite terminals, based on array technologies for Rx and Tx components, will allow to receive and transmit within a certain beamwidth area from different directions employing a multi-element optical array and by introducing variable phase shifts in the signal path of each element. First approaches into this direction are described in e.g. [12], but the system described there lacks the possibility to scan the optical beam in the required range. Designing optical arrays for large scanning angles is considered an area for further investigations.

In contrast to microwave systems, the phased array SDMA concept in optical communication is not mainly driven by spectrum efficiency enhancement, but retains big potential in saving satellite power and system design effort.

These optical phased array SDMA antennas would produce optical spotbeams with diffraction limited divergence angles of some microradians, which for the satellite Tx-terminal would result in at least 10dB additional antenna gain compared to the numbers given above, with at the same time reduced overall Tx-antenna size.

Also a phased-array satellite Rx-antenna would only need one aperture as any optical aberration could be coped with by the Rx beam forming network.

CONCLUSION

In this paper a proof of concept for aeronautical satellite communication with optical terminals was presented.

Using actual flight traffic data for the North Atlantic flight route it was shown that the number of aircrafts to be served by one satellite at a time is moderate and seems manageable.

It was shown that optical communication links have the potential to provide the data rates required to support future broadband applications to airline passengers using at the same time small and power efficient terminals.

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