SLOVENSKI STANDARD
SIST EN 4533-002:2018

01-marec-2018

Nadomešča:
SIST EN 4533-002:2009

Aeronavtika - Sistemi iz optičnih vlaken - Priročnik - 002. del: Preskušanje in merjenje

Aerospace series - Fibre optic systems - Handbook - Part 002: Test and measurement

Luft- und Raumfahrt - Faseroptische Systemtechnik - Handbuch - Teil 002: Tests und Messungen

Série aérospatiale - Systèmes des fibres optiques - Manuel d'utilisation - Partie 002: Essais et mesures

Ta slovenski standard je istoveten z: EN 4533-002:2017

ICS:

33.180.01	Sistemi z optičnimi vlakni na splošno	Fibre optic systems in general
49.060	Letalska in vesoljska električna oprema in sistemi	Aerospace electric equipment and systems

SIST EN 4533-002:2018 **en,fr,de**

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 4533-002

December 2017

ICS 49.060

Supersedes EN 4533-002:2006

English Version

Aerospace series - Fibre optic systems - Handbook - Part 002: Test and measurement

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Ref. No. EN 4533-002:2017 E

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European foreword

This document (EN 4533-002:2017) has been prepared by the Aerospace and Defence Industries Association of Europe - Standardization (ASD-STAN).

After enquiries and votes carried out in accordance with the rules of this Association, this Standard has received the approval of the National Associations and the Official Services of the member countries of ASD, prior to its presentation to CEN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2018 and conflicting national standards shall be withdrawn at the latest by June 2018.

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Introduction

a) The Handbook

This handbook aims to provide general guidance for experts and non-experts alike in the area of designing, installing, and supporting fibre-optic systems on aircraft. Where appropriate more detailed sources of information are referenced throughout the text.

It is arranged in 4 parts, which reflect key aspects of an optical harness life cycle, namely:

Part 001: Termination methods and tools

Part 002: Test and measurement

Part 003: Looming and installation practices

Part 004: Repair, maintenance, cleaning and inspection

b) Background

It is widely accepted in the aerospace industry that photonic technology significant advantages over conventional electrical hardware. These include massive signal bandwidth capacity, electrical safety, and immunity of passive fibre-optic components to the problems associated with electromagnetic interference (EMI). Significant weight savings can also be realized in comparison to electrical harnesses which may require heavy screening. To date, the EMI issue has been the critical driver for airborne fibre-optic communications systems because of the growing use of non-metallic aerostructures. However, future avionic requirements are driving bandwidth specifications from 10’s of Mbits/s into the multi-Gbits/s regime in some cases, i.e. beyond the limits of electrical interconnect technology. The properties of photonic technology can potentially be exploited to advantage in many avionic applications, such as video/sensor multiplexing, flight control signalling, electronic warfare, and entertainment systems, as well as sensor for monitoring aerostructure.

The basic optical interconnect fabric or `optical harness’ is the key enabler for the successful introduction of optical technology onto commercial and military aircraft. Compared to the mature telecommunications applications, an aircraft fibre-optic system needs to operate in a hostile environment (e.g. temperature extremes, humidity, vibration, and contamination) and accommodate additional physical restrictions imposed by the airframe (e.g. harness attachments, tight bend radii requirements, and bulkhead connections). Until recently, optical harnessing technology and associated practices were insufficiently developed to be applied without large safety margins. In addition, the international standards did not adequately cover many aspects of the life cycle. The lack of accepted standards thus lead to airframe specific hardware and support. These factors collectively carried a significant cost penalty (procurement and through-life costs), that often made an optical harness less competitive than an electrical equivalent. This situation is changing with the adoption of more standardized (telecoms type) fibre types in aerospace cables and the availability of more ruggedized COTS components. These improved developments have been possible due to significant research collaboration between component and equipment manufacturers as well as the end use airframers.

1 Scope

This handbook examines the requirements to enable accurate measurement of fibre optic links from start of life and during the life cycle of the system from installation and through-service. Part 2 will explain the issues associated with optical link measurement and provide techniques to address these issues. This document discusses the measurement of key parameters associated with the passive layer (i.e. transmission of light through an optical harness). It does not discuss systems tests e.g. bit error rates.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 2591-601, *Aerospace series — Elements of electrical and optical connection — Test methods — Part 601: Optical elements — Insertion loss*

EN 4533-001, *Aerospace series — Fibre optic systems — Handbook — Part 001: Termination methods and tools*

EN 4533-003, *Aerospace series — Fibre optic systems — Handbook — Part 003: Looming and installation practices*

EN 4533-004, *Aerospace series — Fibre optic systems — Handbook — Part 004: Repair, maintenance, cleaning and inspection*

3 Fibre types

This section gives a brief summary of some of the different fibre types in use within the aerospace industry. Historically, large core, step index multimode fibres were the first to be used on aircraft. At the time of design, these fibres enabled sufficient data bandwidth and the large core enabled ease of coupling (of light) into the fibre as well as ease of fibre alignment in connectors (also termed interconnects). Therefore in some current and legacy systems, fibre optic harnesses based on large core fibres can be found. Common larger core fibres include 200/280 µm, 200/300 µm and 100/140 µm (where the notation indicates the core/cladding size).

Improvements in bandwidth (mainly from reduced temporal dispersion), for multimode fibres is possible by using graded index fibres. In simple terms, the graded refractive index profile allows equalisation of different optical paths through a multimode fibre to reduce any pulse spreading in time (dispersion). These results in higher bandwidths compared to step index refractive index profiles. Early graded index fibres for aerospace included 100/140 µm sized fibres.

More recently, fibre sizes commonly used in the telecoms and datacomms fields have been utilised for aerospace. Multimode fibres of size 62,5/125 µm and 50/125 µm and with graded index profile are now being deployed for data transmission on both civil and military aircraft, fixed wind and rotary craft. Fibres are available with different bandwidths. Multimode fibres are designated by the OM identification (meaning 'optical multimode'). OM1 describes 62,5/125 µm fibre, OM2, OM3 and OM4 describe 50/125 µm fibres of increasing bandwidth. Using these sizes of fibre (particularly with a 125 µm outer diameter enables the use of volume production parts (e.g. ceramic alignment ferrules) from the telecoms industry.

As will be discussed in this document, the issue of test and measurement in multimode systems is complicated by the light distribution in the fibre and also the relatively short length of installed fibre which typically has several connector breaks in the harness path (e.g. connectors located at airframe production breaks). The light distribution launched into the fibre to make measurements is critically important for making consistent measurements in multimode systems.

Whilst most of the deployed fibre in aerospace is currently multimode, there is increasing interest in using singlemode fibre. Single-mode (sometimes called monomode fibres) are optical fibres designed to support only a single propagation mode per polarization direction for a given wavelength. They usually have a relatively small core (with a diameter of only a few µm's) and a small refractive index difference between core and cladding. The mode radius is typically a few microns.

Singlemode fibres are often termed OS1 (for 'optical singlemode'). There are also other types of singlemode fibre as OS2 and A2. The small core enables many benefits to be realised (e.g. higher bandwidth (minimal dispersion), wavelength multiplexing, novel sensor applications). However the smaller core makes the coupling and alignment more difficult at the source and at connectors (particularly in the harsh aerospace environment with potential extremes of temperature and vibration).

The issue of test and measurement in singlemode fibres is not as complicated as for multimode systems. This is principally because the light travels down the fibre in a predominant single mode or path.

It should be remembered that the optical fibres discussed above will be packaged in rugged cable form suitable for installation and performance on a harness. More detail of cable constructions can be found in Part 001 of the EN 4533 standard. It is further noted that modern fibre optical cable designs are now utilising bend tolerant optical fibres and a number of aerospace designs exist. These exhibit lower losses when bent to a small radius (A2 fibre).

Test and measurement in glass fibre multimode systems will generally use LEDs or multimode VSCSELs as the test light source. Test and measurement in singlemode glass fibre systems will generally use semiconductor lasers or newer singlemode VCSEL light sources. The common transmission wavelengths used for glass multimode fibres are 850 nm (sometimes 1 300 nm). Glass singlemode systems generally use 1 550 or 1 300 nm transmission wavelength.

For completeness it is noted that plastic optical fibre (POF) is being considered for some applications in aerospace. However at the present time, the TRL of this technology is much lower than for glass fibre (at least in an aerospace environment). POF is generally much larger than glass fibre e.g. with size 980/1 000 µm. This large core makes coupling and connector alignment much easier. However POF is much more lossy (higher attenuation) than glass fibre and works best with visible transmission wavelengths (typically in the 520 nm to 650 nm region).

4 Test and measurement: key parameters

4.1 Insertion Loss (I.L.)

Insertion loss is probably the most frequent measurement performed on a fibre optic component or link/ harness during its life cycle.

When an optical device, component or fibre section is inserted into an optical link, some of the optical power will be lost in the device (e.g. a splitter) or at optical interfaces (e.g. at a connector or splice). Fibre sections will also introduce a loss albeit small (the attenuation at the common transmission wavelength for glass fibre is very low).

Some of the optical power will be lost due to non-perfect interfaces e.g. reflective surfaces or scattering. Another aggravating factor is misalignment in connectors. Such misalignment can be lateral, axial or angular. Contamination will also impact on the insertion loss (dirty connectors will have higher loss than clean connectors).

The insertion loss (or attenuation) is usually specified in decibels, calculated as 10 times the logarithm of base 10 of the ratio of input power (*in*) to the output power (*out*). For fibre connectors, for example, it is often of the order of 0,2 dB. High-quality fusion splices may reach values like 0,02 dB.

$\text{I.L.} = 10 \log_{10} (P_{in}/P_{out})$

e.g. for a transmission of 90 % (0,9), the insertion loss would be 0,46 dB.

4.1.1 Importance of low insertion loss

Clearly for efficient light transmission, a low insertion loss is desired. This means that only a small amount of light will be lost at the component or link under test. The system power budget will generally dictate how much power needs to be transmitted through the link from source to receiver. The difference between the source power and the minimum required receiver power will give a power budget figure. The total insertion loss of the components must not exceed this value. It is also useful to have a safety 'margin' to allow for system degradation and ageing. A 3 dB ageing margin is typical for aircraft links.

4.1.2 Measurement techniques

Various methods exist for measuring insertion loss depending on the type of component and whether it is connectorised. These are detailed in the EN standard EN 2591-601. In terms of equipment, insertion loss can be measured with a fibre optic light source and power meter arrangement or more sophisticated equipment such as an OTDR or OFBR (discussed later in 6.1 and 6.2) can also be used.

An important point to emphasise particularly for multimode systems is that the insertion loss measured for a component, fibre section or complete link will depend on the light distribution in the component (and the launch light distribution from the source). This means that if two different light sources (e.g. from different manufacturers) are used to test the insertion loss it is possible that different insertion loss values will be obtained. This makes it difficult to design systems using test data on components alone especially where the method used to make measurements is not specified.

5 of this document will discuss how launch conditions can be practically controlled to ensure consistency in test and measurement in multimode systems.

9.2 discusses some aspects of practical insertion loss measurement.

4.2 Return or reflection loss

The return loss R.L. (or reflection loss) of an optical device or link gives a measure of how much light is reflected back to the light source compared with the amount of light sent into a system.

R.L. is defined by:

R.L. = $10 \log_{10} (P_{in/}\ P_{refl})$

Usually, the return loss is specified in units of decibels. For example, if the return loss is 30 dB, the returning light has only 1/1 000 of the power of the incident light. Note only directly returned light is measured – and not light which is reflected into a different direction, e.g. at an angle-cleaved fibre end. RL is a positive number, and a high RL means that only a small amount of power is reflected from the link. The power values are generally measured in Watts or mW (noting that all powers should be in the same units. For lower amounts of reflected light, the return loss therefore becomes a larger number (e.g. 1/5 000 power reflection is 37 dB return loss). Developing this idea further a perfect device or component with infinite return loss would reflect no light back towards the source. In reality, real devices will have a finite return loss.

In avionic applications, due to the short link lengths employed, the back reflected power from the fibre itself is very small with respect to the reflected power from optical connectors. That said mated connectors such as UPC and APC (Ultra Physical Contact and Angled Physical Contact) can also have extremely small return loss in the region of ~ 55 dB to 65 dB (values for singlemode fibre).

4.2.1 Importance of high return loss

Some systems (particularly using single-mode and single-frequency lasers), are sensitive to back-reflected light. If too much light is reflected this may destabilise the laser operation and cause excessive laser noise and/or emission on multiple optical frequencies. In high speed optical fibre communications, back-reflected light may ultimately increase the bit error rate.

4.2.2 Measurement techniques

As for insertion loss, there are different methods available to measure the return loss. Methods are detailed in the standard EN 2591-605 (Return Loss). A typical method uses a coupler device (e.g. a 50:50 splitter) to introduce light into a system and also route the reflected light to a power meter. This European Standard is currently being reviewed and updated to include the latest techniques for measuring return loss with return loss meters, OTDRs and OFDRs (optical time domain and optical frequency domain reflectometer instruments respectively).

4.2.3 Return loss versus reflectance

It is important to include a note on terminology as different terms may be encountered in different texts. Return Loss is generally used to describe the amount of reflected light from an optical assembly. This may be composed of discreet elements (e.g. connectors, fibres, couplers, splices etc.). Another term that may be seen is Reflectance. The Reflectance of a connector or of any other type of reflective event in the fibre (e.g. a kink, damage, or discontinuity) is generally defined for **a single discrete event**. If we denote by P_{ref} the reflected power. Reflectance is defined by:

Reflectance = $10 \log_{10} (P_{ref}/P_{in})$

Reflectance is a negative number (the reflected power is less than the incoming power), and a lower Reflectance means a better connector. In the case of a single reflecting event in an assembly, both RL (of the whole assembly) and Reflectance (of the event) represent the same parameter, with opposite signs.

IMPORTANT NOTE Reflectance or RL of a single event represent the same parameter, with opposite signs, Reflectance being a negative number and RL being a positive number. Accordingly, a good connector must have low reflectance (negative value) or equivalently high RL (positive value).

9.6 discusses some practical aspects of return loss measurement.

4.3 Optical power measurement

Optical power may need to be measured at various points in a fibre link. Power values are important in assessing the output from a light source or data transmitter. Power at the end of a link (before a detector) will determine the received power and this will determine the performance of the system. Power measurements feed into the main calculations of insertion loss and return loss.

Power is normally measured in units of Watts although power levels in fibre systems are typically in the mW region. It is also common to see power measured in dBm units. These are defined as follows:

Power (dBm) = $10 \log_{10}$ [Power (Watts)/10^-3(Watts)].

Thus a power of 1 mW would equate to 0 dBm. Powers less than 1 mW would be negative (e.g. 0,5 mW = – 3 dBm). A power of 2 mW would be + 3 dBm.

4.3.1 Measurement techniques

Optical power in fibre optic systems is routinely measured using power meters (see Figure 1). These are portable instruments usually with a fibre optic interface (to allow connection of different connector types to the meter). Most power meters will have the option to display the optical power in units of Watts or dBm. Some instruments will also allow a power to be held as a reference power. Following the referencing operation, the power measured after this is displayed as a dB loss (compared to the reference power value). This can be useful for measuring insertion loss of components.

Figure 1 — Benchtop and portable optical power meters

Power meters may be used in conjunction with couplers to measure return loss. Return loss meters are available that integrate the coupler and power meter components (and sometimes an optical source).

4.3.2 Photodectors requirements

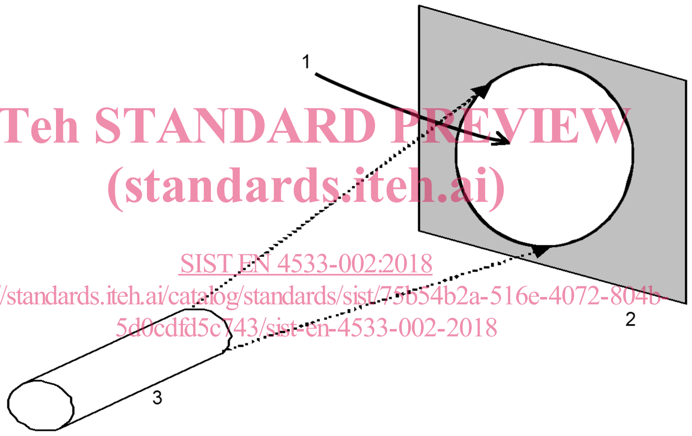
Power meters will have an active detection area. This should be large enough to collect all the light emerging from the fibre under test (linked to the NA of the fibre). Thus the distance to the active detector element should not be too small so that some of the power is not captured (see Figure 2). This may only be a problem in very large NA fibres or possibly in large core POF fibre. This problem can be managed if the power meter uses an integrating sphere. In some cases it may be important to only collect light within a given distribution or angular spread. An example might be where a data receiver has a smaller area or is fibre coupled (having a short section of fibre from a detector to the active receiver element). In these cases a test lead at the receiver end can be useful in restricting the detected power. Measuring the power with a large area detector may over-estimate the useable system power at the receiver.

Another other important aspect of power measurement is the accuracy of reading. Power meters should be calibrated regularly to ensure that the power displayed is correct (traceable to national standards). Most instruments will also have the facility to select a measurement wavelength (this will commonly be one of the main glass fibre transmission wavelengths (e.g. 850 nm, 1 300 nm, 1 550 nm) although some power meters (using different detector materials) can measure at other wavelengths (an example might be 650 nm used for POF systems).

If the power meter readings are to be used to infer insertion loss or return loss values, then it is important that the power meter has a linear response (the absolute power measurement accuracy is then not critical as the calculation uses a ratio of power readings).

It is also worth noting that the power emitted says from an LED or laser source may not all be coupled into a fibre. The fibre will have an acceptance angle (defined by the NA). In some cases it may be important to know the ‘fibre coupled’ power, i.e. how much useful light is guided by the fibre. This measurement may therefore use a section of fibre connected to the light source with the power then measured at the fibre end.

Power meters detect light with an active photodetector usually based on semiconductor material. Common types are Silicon, Germanium and Indium Gallium Arsenide. These materials have different responsivities at different wavelengths. In the specific case of a photodetector, responsivity measures the electrical output per optical input. The responsivity of a photodetector is usually expressed in units of either amperes or volts per watt of incident radiant power. For most aerospace multimode systems at 850 nm, Silicon PIN photodiodes will be used. These have very good spatial and angular uniformity. The detector can have a filtering effect on the power distribution if its response varies across the area of the detector or varies with the angle of incidence of the light. This may be worse at longer wavelengths but effects will be detailed in manufacturer data sheets.



Key

1 Area of projected beam from the fibre

2 Detector area

3 End of fibre

Figure 2 — To prevent the detector in the power meter from filtering the power distribution, the detector has to be larger than the projected beam of light coming from the fibre of the test lead

It should be ensured that the power meter is capable of detecting power at the wavelength(s) in the system under test. The maximum power level in the system should be detectable under test without saturation. Also, the power meter should have enough dynamic range to enable correct measurements to be made at both high and lower power levels. At very low power levels, noise levels may become important to consider.

It should be remembered that power meters generally measure the average power that is detected (e.g. if detecting a data modulated light source) although for much of the standard testing (e.g. insertion loss, back reflection) a cw (continuous wave) source or light launch system will be used.

The refractive index of the materials that are used as detectors is generally high and this means that a proportion of the light that strikes a detector is reflected. This light can be reflected back onto the detector by the surroundings and the power reading will be anomalously high. Blacking the surroundings of the detector will minimise their reflectivity and improve the accuracy of the power reading. Fibre adapters used to hold the fibre connector in front of the detector are generally black for this reason.

4.4 Light distribution

Although not a routine measurement on installed optical harnesses, it may be necessary to measure the light distribution e.g. from a source or fibre. Light distributions are critically important especially for test and measurement in multimode systems where the distribution of light can influence measurements such as insertion loss. These effects are discussed in more detail in Clause 6 later on. It can be difficult to measure the near and far-field distributions of some sources like LEDs because the packaging can obscure some of the emitted light. The distributions can only be measured after passing through a short length of optical fibre.

Detector arrays (e.g. CCD) may be used along with an imaging system to detect the spatial profile of light emerging from a system under test. Such systems may also use software to determine the 3D distribution of light. Alternatively scanning the imaged system with a single detection system (e.g. pinhole, slit or fibre linked to a power meter) may allow slices across the optical distribution to be measured. Systems are also available to automatically measure the near field profile of fibres and fit distributions to pass/fail temples.

4.5 Temporal measurements

For measurements that require temporal detection of the light system e.g. measurement of data rates, bandwidth, modulation effects, Bit Error Rate (BER) etc. the light detection system will then generally be a fast optical detector (with bandwidth capable of detecting the highest data rates). It will usually be used in conjunction with specialist measurement equipment (oscilloscopes, BER test equipment, signal analysers for example) to derive the appropriate measurement parameters. Exact details are beyond the scope of this European standard. Generally however, the fast detector will have a front end featuring a fibre optic interface to allow the system under test to be coupled.

5 Test and measurement in single-mode systems

For singlemode fibre systems, because the light travels down the fibre in a dominant single optical mode, measurements are not generally dependent on the launch condition into the fibre. The transverse intensity profile at the fibre output generally has a fixed shape, which is independent of the launch conditions and the spatial properties of the injected light, assuming that no ‘cladding modes’ can carry substantial power to the fibre end. The launch conditions only influence the efficiency with which light can be coupled into the guided mode.

Singlemode fibres are characterised by a physically small core size (typically ~ 9 µm). They guide in a singlemode regime within a certain wavelength range. These types of fibre have a single-mode ‘cut-off’ wavelength, beyond which the fibre supports multiple modes.

Although real applications of singlemode fibre are only just starting to be seen in aerospace systems, singlemode fibres will generally use ‘standard’ telecoms wavelengths e.g. 1 300 nm, 1 550 nm. Sources are typically lasers. Longer wavelength VCSELs are starting to emerge for single-mode application. For test and measurement, small compact cw (continuous wave) lasers at these test wavelengths are available. Note that many multimode aerospace systems use a shorter wavelength of 850 nm because reliable and rugged sources (LEDs and VCSELs) are available at that wavelength and attenuation is still low at this wavelength (aerospace platforms are relatively short and do not require ultra-low attenuation as might be required for long haul links).

Efficiently launching light into a single-mode fibre requires that the light beam is of high quality (ideally the M^2 beam quality factor should be close to a value of 1) and that the light has a focus at the fibre input end (for matching to the fibre mode) as well as being axially and angularly aligned to the fibre core and axis. Any error in position must be well below the beam radius, and the angular misalignment must be small compared with the beam divergence of the mode.

6 Test and measurement in multi-mode systems

Test and measurement in multimode systems is more complicated than for singlemode. This is because the measurements made depend on the light distribution within components and fibres.

6.1 Launch conditions

The input launch condition into a multimode fibre system is especially important. In simple terms, different light sources can have different launch conditions and this can lead to different measured values e.g. of insertion loss. Clearly this is undesirable. Further, the insertion loss of a particular component can also depend on its position within the link if launch conditions are not controlled.