OUTCOMES FROM THE JRC-ESA JOINT WORKSHOP ON ADVANCED PV MEASUREMENTS AND RELIABILITY

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Abstract

This report summarises the topics and the discussions held at the workshop on "Advanced PV Measurements and Reliability", which was organised jointly by the European Solar Test Installation (ESTI) of the European Commission's Joint Research Centre (JRC) and by the European Space Technology and Research Centre (ESTEC) of the European Space Agency (ESA). This workshop was one of the collaborative initiatives falling under the administrative agreement signed in 2013 between JRC and ESA.

The workshop on "Advanced PV Measurements and Reliability" was held online on 11th and 12th November 2020, with more than 50 participants from both space and terrestrial PV communities and a balanced representation between them. Participants were from PV calibration and testing laboratories, national metrological institutes, university, public and private research centres, as well as manufacturing companies of PV cells, instrumentation and services. The areas covered by the workshop were the reliability of PV cells and ensembles, the standardisation for PV and the state-of-the-art best practices in the characterisation and calibration of PV cells, assemblies and modules. Good practices as well as present and foreseeable future challenges were reported and discussed. Some conclusions and recommendations on future collaborations and activities were drawn, too, and are presented here.

1 Introduction

1.1 Context

The collaboration between the European terrestrial and space photovoltaic (PV) communities, which started some decades ago, was renewed in 2013 by an administrative agreement between the former Institute for Energy and Transport ([1]) of the European Commission's Joint Research Centre (JRC) and the Technical and Quality Management Directorate of the European Space Agency (ESA). Such an agreement covered a range of fields in which both institutions were and are still active, including PV. In the field of PV, this meant to open the way to a renewed collaboration between the JRC's European Solar Test Installation (ESTI) and the ESA's European Space Technology and Research Centre (ESTEC).

Within this cooperation framework, the first workshop on "Space and Terrestrial Photovoltaics Reliability" was organised jointly by JRC and ESA and held at ESA-ESTEC in September 2013.

The workshop on "Advanced PV Measurements and Reliability", whose recommendations are summarised in this report, was the concluding task of the above mentioned agreement. In particular, the workshop aimed at gathering together experts on the reliability of PV devices from both PV communities, as originally included in the underpinning agreement. However, as PV as well as its characterisation and deployment have substantially evolved in the last ten years, the workshop was organised to cover additional topics, too, which are currently at the centre of the research activities of both PV communities. They include the standardisation activities carried out at the relevant international standardisation organisations; the metrological chain that ensures meaningfulness and reliability to all subsequent PV testing; and the advanced characterisation of PV cells and assemblies at standard and non-standard test conditions. As discussed in this report, these could be a more promising ground on which to base further PV growth and mutual benefit of both communities.

1.2 Terms and definitions

Before entering the details of the topics explored in this workshop, some general definitions are necessary in order to set the terms that are used throughout this report. Although most of the terms are common to both PV communities, some of them are specific to the target application. As such, they are summarised here to ease the understanding of the following sections.

The core of terrestrial as well as of space PV is the PV cell, which can be made of one single photoactive junction to convert light into electricity or more. In the former case, the PV cell falls under the definition of single-junction (SJ) PV technologies, to which for instance crystalline silicon (c-Si) and cadmium telluride (CdTe) belong. In the latter case, the PV cell is part of the multi-junction (MJ) PV technologies, which include for example the III-V MJ cells ([2]) used in space PV and in terrestrial concentrating PV (CPV).

When the PV cells are assembled together to form what is generally called here a PV assembly or PV ensemble, terrestrial and space communities use different terms and as such they are applied in this report, too:

— in terrestrial PV, the typical assembly of PV cells ready to be deployed in the final application is called PV module;

— in space PV, the final overall assembly of PV cells is called PV assembly (PVA), defined as a "power generating network comprising the interconnected solar cell assemblies, the shunt and blocking diodes, the busbars and wiring collection panels, the string,

([1]) Today, the Directorate of Energy, Transport and Climate.
([2]) III and V represent the groups of chemical elements in the periodical table of elements.

section and panel wiring, the wing transfer harness, connectors, bleed resistors and thermistors" ([3])([4]).

Thus, terrestrial PV modules correspond to space PV assemblies for the purpose of this report and its discussions. To keep the term general, any assembly of PV cells that does not reach the status of final assembly definitions as given above is named sub-assembly here.

1.3 Overview of the workshop and of this report

The workshop was organised in three main sessions:

1. ***Reliability session***, to look for and discuss about reliability and long-term resistance tests and methods of common interest and application (see section 2.1). The core part of this session covered research activities that are traditionally looked at in connection with the reliability of PV, because they address and aim at preventing well-known failure modes. They are:

   (a) the lifetime testing until component failure;

   (b) the thermal cycling at component as well as (sub-)assembly levels;

   (c) possible testing methods for long-term storage and feasibility of defining acceleration factors.

   Beside these, though, the session explored another topic that can seriously affect the reliability of terrestrial PV modules and space PV assemblies if not addressed adequately. This is the electrical mismatch between the cells of a generic PV assembly. As the PV cells are selected to be as well-electrically matched as possible during the production of this PV assembly, the electrical mismatch can originate from different causes depending on the surrounding environment in which the PV assembly is deployed. Important sources of electrical mismatch are the partial shading and/or the PV cells' physical damage. The reliability session was thus organized to share also knowledge and experience on how these sources of PV failures are currently dealt with in each community.

2. ***Standardisation session***, to share the latest updates and on-going key topics of common interest in the standardisation activities of both PV communities (see section 2.2). It also aimed at collecting any possible issue or topic to be reported back to the relevant standardisation organisations.

3. ***Characterisation session***, to share the state-of-the-art practices of advanced electrical performance measurements, with particular but not exclusive attention to MJ PV devices. This covered:

   (a) the metrological PV traceability chain, from solar irradiance measurements to the final device under test;

   (b) the good practices for PV measurement developed and adopted by space and terrestrial PV communities, with a special focus on MJ PV devices;

   (c) the issue of an explicit definition of spectrally-matched reference cells, which at present is missing in any published international standard;

   (d) the spectral irradiance measurements and the spectral mismatch issues under simulated and (either terrestrial or extra-terrestrial) natural sunlight;

   (e) the advanced characterisation methods to test PV devices at non-standard conditions of irradiance and temperature.

([3]) For space PV, a solar cell assembly is a "solar cell together with interconnector, coverglass and, if used, by-pass diode". (source: https://ecss.nl/item/?glossary_id=2650)

([4]) Source: https://ecss.nl/item/?glossary_id=1555

Each session was structured to include the perspective and the experience of each PV community on each covered topic, in order to share know-how and possible solutions to common present or foreseeable future challenges. The workshop's agenda is reported in Annex 1.

The structure of this report follows the workshop's subdivision. Section 2 is divided in three main sub-sections, each of which deals with one of the sessions listed above. The main topical elements and the key session conclusions and recommendations are reported there. An overall summary of the workshop's outcomes and recommendations is given in the concluding section 3.

2 Work and outcomes from the joint JRC-ESA workshop

This report is structured in three subsections, each of which deals with one of the areas discussed at the workshop, i.e. reliability, standardisation and characterisation of PV. Each subsection includes a summary of the main topics that were presented during the corresponding session of the workshop as well as a closing summary of the session's conclusions and recommendations.

2.1 Reliability session

Reliability of PV devices is clearly a crucial topic for both space and terrestrial PV communities. Reliability in its wider meaning is not simply a pass/fail qualification of a device. It entails the capability of predicting with an acceptable degree of confidence the resilience of a PV device to some environmental conditions and stressors, for the entire period during which the power-supply service has to be delivered. This period of time is also named operational lifetime. If the PV reliability is inadequate, it can disrupt the operation of the system(s) to which the PV devices supply the electrical power.

Each PV community has to face and find solutions for stressors that are specific to the environment where the PV devices will be deployed. However, as explained below, both PV communities have to mitigate the performance degradation of the PV devices caused by excess heat and by terrestrial atmospheric stressors, in particular atmospheric humidity. The reliability session was centred around these two major topics, but it also covered the issue of electrical mismatch between the cells inside a PV assembly. The latter had remained excluded from a joint discussion until now, but it could become a point of possible mutual interest and support.

2.1.1 PV reliability in terrestrial applications

Terrestrial PV is constantly exposed to a range of environmental stressors that originate from the surrounding terrestrial atmosphere. These stressors can be of chemical, physical or chemo-physical nature. Regardless of the atmospheric composition to which it is exposed, terrestrial PV is subjected to thermal and radiative stresses due to its installation conditions and to its exposure to the natural sunlight.

Besides protecting PV cells from the environment, terrestrial PV has to constantly guarantee also the safety of persons and animals as well as the protection of the environment against any harm that could be caused by the PV assembly itself.

Therefore, terrestrial PV is typically encapsulated inside a sealed package. This helps limiting the degradation of the electrical performance due to humidity and, at the same time, ensures an electrical insulation of the active PV components towards the outside. Humidity indeed is a major stressor for terrestrial PV components, causing their oxidation or delamination. It can also produce a shunted path between active surfaces that should not be directly connected electrically, with loss of performance and safety of the PV module.

Another major stressor for terrestrial PV modules is temperature, both in its absolute value and in its daily variations. First of all, a decrease in electrical performance is observed in most PV technologies as a consequence of the temperature increase; among them, crystalline silicon (c-Si) is one of those with larger performance variation due to temperature. Secondly, the encapsulant and many of the packaging materials are based on polymers, whose physical properties could be seriously altered by exposure to excessive temperatures above as well as below 0 °C, for example beyond their melting or embrittlement points.

Therefore, accelerated stress tests for terrestrial PV have been systematically developed and refined in time, in order to prevent and limit failure modes observed in the field and linked to environmental stressors. The latter are rarely present as single factors and their effects can be enhanced by the installation conditions. Quite often a combination or a sequential occurrence of different stressors leads to a failure of a terrestrial PV module.

The confidence in the reliability of terrestrial PV modules is thus determined by passing the relevant standardised stress tests, some of which are applied only for specific final applications. The current series of standards IEC 61215 [1] collects the principal stress tests that terrestrial PV modules have to pass for their design qualification and type approval, including those related to exposure to specific ranges of humidity and temperature and of their combination.

Among other causes of performance losses and failure modes besides humidity and temperature, the partial shading is one strictly connected to the actual installation layout of the PV modules and systems. The partial shading occurs when only part of a cell or part of a module is fully illuminated by the sunlight, with the rest in the shade. This produces a reduction in the performance of the shaded components, which affect the performance of the entire string of PV cells or PV modules. In severe cases and depending on the PV technology, the partial shading can also lead to a localised increase in the temperature of the shaded areas, with various consequences ranging from materials' deterioration only to a fire ignition. Partial shading can be caused, for example, by an obstacle that is located between the PV module and the sun for a short-term period only, like for example a chimney or an antenna, or by long-term soiling and other accumulation of material on part of the front surface of the PV module, like for example dirt or snow.

The increasing amount of PV systems installed in a broad range of environmental conditions, or in residential contexts where shading from surrounding objects is unavoidable, has pushed to find different solutions to this problem. The use of half-cells parallel strings with their own dedicated diode is becoming the most adopted. An accurate modelling of the PV modules layout as well as of the individual PV systems can also help reducing the occurrences of performance losses due to partial shading.

2.1.2 PV reliability in space applications

PV for space applications typically operates in absence of any atmosphere. In addition, the mass of every single piece of equipment launched during each mission has to be kept to the minimum value possible to limit the fuel consumption and the overall cost of the mission itself. Therefore, contrary to terrestrial PV, PV for space is not encapsulated, but only protected by a transparent glass that is attached to the cell by a transparent adhesive. As such, it can be exposed to a variable amount of humidity and to terrestrial atmosphere before launch.

This exposure is strongly reduced by storing PV cells and space PVAs under controlled ambient conditions, e.g. gaseous nitrogen atmosphere, before their use. However, it cannot be avoided during some operations of the space mission, for instance those necessary to prepare and launch the rocket that carries the PVAs to their final destination in space.

Although limited in time, this exposure can be a source of partial degradation of the unencapsulated PV cells, already before they are put in operation. This implies that, for space applications, PV resilience towards the exposure to terrestrial atmosphere and its humidity has to be tested and validated. Indeed, space PVAs have to guarantee the energy supply that is necessary to operate all the critical systems of a spacecraft for the entire duration of the mission. No easy or cheap maintenance is possible after their launch.

Once in operation in space, though, PVAs are exposed to other types of stressors, which can reduce their lifetime and their performance. Some types of stressors are common to terrestrial PV, e.g. temperature; others are specific to space environment, e.g. highly energetic particles ejected by the sun and captured by the Earth's magnetic field or the increasing amount of space debris orbiting around the Earth.

For what concerns thermal stress, the range of temperatures that a PVA can encounter in space is typically larger than at ground. Temperatures as high as 200 °C or as low as -240 °C can be met, depending on the distance from the Sun and on the exposure of the PV array([5]) towards it. The thermal cycles adopted in the reliability tests for space PV have to reflect these extreme conditions.

Depending on the mission, the spacecraft specific manoeuvres and/or the appendages of the satellite can result in a temporary partial shading of the PV cells. Such a shading can cause a temporary electrical mismatch between the cells of the PVA, with consequences similar to what occurs in PV modules and systems in terrestrial PV. Furthermore, the impact of highly energetic particles or space debris can alter the physical structure of the PV cells, with consequent damage and reduction of their electrical performance. As a consequence, an electrical mismatch can also occur between the cells of a PVA under these circumstances. Such a mismatch can result in an unwanted reverse operation of the shaded solar cells, which in turn could lead to their irreversible damage. Therefore, each solar cell is protected by a dedicated diode.

2.1.3 Workshop's conclusions on PV reliability activities

The discussion that took place at the end of the reliability session brought to the conclusion that PV reliability has to face quite different challenges in space and in terrestrial applications. In both cases, PV devices are subjected to some stressors (or stressing agents) that can degrade their performance. The degradation can turn into a failure if the stressors are strong enough or if they last long enough. However, the types of stressors are quite specific to either space or terrestrial environment and little can be put in common between the two communities on the topics traditionally discussed. Some conclusions for further steps and some recommendations have been drawn and are reported here.

The exposure to terrestrial atmospheric humidity, which could be considered a condition common to PV assemblies of both communities, has in fact different effects on terrestrial PV and on space PV. The former is indeed encapsulated to limit as much as possible humidity contamination inside the PV device. As such, the accelerated stress tests developed for terrestrial PV already ensure – with high level of confidence – that the packaging is adequate to protect the active parts of the PV device from vapour water for an expected operational lifetime of at least 25 to 30 years. Space PV, instead, is exposed for a very limited time to humidity compared to terrestrial PV. However, this little amount of humidity can still be an accelerator agent of failures. Therefore, a dedicated humidity test is part of the qualification of space PV in order to validate that no degradation occurs due to humidity and terrestrial atmosphere.

Finally, the storage conditions should be carefully considered in both the conception and the development of tests and standards aimed at assessing the PV reliability. This is certainly valid for space PV, for what discussed above, but it could also be useful for terrestrial PV.

In conclusion, building a common approach to test traditionally-explored common stressors was proved not as straightforward or feasible as it was largely considered before this joint discussion. However, other elements of the session and of the discussion opened new possibilities of mutual support and knowledge sharing.

One of them is the common need for modelling thermal cycles, which should be adequate for the specific application. Both PV communities are working on extending the temperature ranges of their thermal stress tests and might also need to optimise them for the specific PV installation (terrestrial PV) or missions (space PV). In this context, preliminary computational simulations might help to avoid PV layouts or configurations that result a priori in a high probability of failures.

Another possible future synergy is the modelling activity to optimise the performance of PV assemblies under electrical mismatch conditions, due to partial shading or other

([5]) A space PV array is an "assembly of solar panels on a supporting structure with associated hardware" (Source: https://ecss.nl/item/?glossary_id=2648) causes. Until now, this had not been considered a topic to share, but during the discussion it resulted to be a feasible one and as such it should be deepened.

2.2 Standardisation session

Terrestrial PV and space PV are tested according to specific international standards. For terrestrial PV, these are generally the standards developed by the Technical Committee 82 (TC82) of the International Electrotechnical Commission (IEC). In some cases, and only binding for the European Union's member states, they are specifically developed by the Technical Committee 82 of the European committee for electrotechnical standardisation, CENELEC. The agreement in place between IEC and CENELEC facilitates the adoption – by one organisation – of a standard developed by the other ([6]); however, there is no obligation to do so, especially if specific requirements make the fast lane of the direct parallel adoption inappropriate. For space PV and for topics that are agreeable at international level, the standards are developed at the International Standardisation Organisation (ISO), although with large reference to the IEC standards whenever possible, thanks to the mutual recognition between the two standardisation bodies. To a large extent, space PV relies on regional standards, which in Europe belong to the series developed under the European Cooperation for Space Standardisation (ECSS) ([7]).

The workshop's standardisation session focused on the latest activities on the drafting and the revision of four critical international standards for PV testing:

- The ISO 15387 [2], which deals with the measurement and calibration procedures for space PV solar cells. It is currently being considered for revision in connection to the recent scientific revision of the AM0 reference spectrum ([8]) [3];
- The IEC 60904-1-1 [4] and the IEC 60904-8-1 [5], which are the standards for testing and calibration of terrestrial MJ PV devices, published in their edition 1.0 in 2017 but still to be adopted by some testing laboratories in terrestrial PV;
- The IEC 60904-9 [6], which is the standard according to which the solar simulators for PV testing are characterised and classified for terrestrial PV. It is also used to a large extent by the space PV community, with some adaptations as described in the ISO 15387. The IEC 60904-9 was recently substantially revised and the new edition was published in 2020.

2.2.1 ISO 15387

The standard for space cells measurement and calibration is currently being considered for revision by the space PV community in order to make it suitable for the state-of-the-art measurement procedures and scope, also taking into account recent updates in the solar measurements evaluation [3, 7] and in the total solar irradiance (TSI) value [7].

The new scope of the standard should be extended to MJ PV cells, as these represent the most common PV technology currently employed in space applications. Moreover, the distinction between the requirements for measurement and those for calibration of PV solar cells should be reflected in the clear separation of the topics in two documents. ISO 15387 should only deal with the <u>calibration</u> of PV solar cells for space applications. Finally, the applicable procedures for the <u>primary calibration</u> of these cells should include in the next edition only those methods that are based either on measurements performed at high altitude ([9]) in the atmosphere (balloon or aircraft flights), or on the differential spectral responsivity (DSR) measurements with subsequent calculations

([6]) The long-lasting cooperation between CENELEC and IEC was started in 1996 by the Dresden Agreement and has been renewed by the currently valid Frankfurt agreement, signed on 17 October 2016 (source: https://www.cenelec.eu/aboutcenelec/whoweare/globalpartners/iec.html).

([7]) The European Cooperation for Space Standardization is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities. (source: https://ecss.nl/)

([8]) AM0 is the solar spectrum as measurable outside the limit of the terrestrial atmosphere, i.e. the extra-terrestrial spectrum at air-mass zero.

([9]) Above 30 km.

carried out by using AM0 as reference spectrum. The removal of the ground methods ([10]) from IEC 60904-4 [8] for the primary calibration of space PV would be a major technical change compared to the present valid edition of ISO 15387. However, this change is considered necessary by the space PV community in order to ensure an acceptable uncertainty of PV cells' primary calibrations under AM0 spectrum.

Another major technical change of the next edition should involve the revision of the AM0 solar spectrum itself. This is a consequence of recent updates in the understanding of the TSI value, which has been changed from the original 1367 W/m^2 to the new 1361.1 W/m^2 on the basis of careful analysis of some decades of solar measurements [7]. The change in the TSI value in combination with recent solar irradiance measurements has also led to a revised determination of the solar spectral distribution present outside the terrestrial atmosphere [3], which is ultimately the AM0 spectrum. The AM0 spectrum as tabulated in the ISO 15387 should also become a normative element of the standard itself – analogously to what the AM1.5 reference spectrum [9] is for terrestrial PV –, while in the currently valid edition the spectral distribution of AM0 is only an informative element of the standard.

Finally, the characterisation of the solar simulators is necessary for the secondary calibration of MJ PV solar cells. Such a characterisation is based on the standard IEC 60904-9 [6], which is aimed at terrestrial PV. Therefore, the IEC 60904-9 requirements for the spectral irradiance classification of solar simulators are tuned for space PV applications in the ISO 15387, in order to increase the resolution of the wavelength bands' binning as well as the overall spectral range to be checked. This is strictly connected to the fact that MJ PV solar cells with three or more junctions are used in space PV applications much more than in terrestrial PV. These MJ PV cells overall respond on a broader spectral range ([11]) compared to common SJ PV and concurrently their individual junctions show steep edges in a narrower spectral responsivity (SR) range. Therefore, the adjustment of the solar simulators' spectrum to the reference spectrum has to be adequately ensured for the overall as well as for the individual spectral ranges.

If approved in its revised edition, the ISO 15387 will thus integrate and adjust the requirements of the IEC 60904 series of standards, which is explicitly aimed at terrestrial PV, to meet specific requirements that are relevant for the calibration of SJ and MJ PV solar cells for space applications.

2.2.2 IEC 60904-1-1 and IEC 60904-8-1

In 2017, two new standards – namely IEC 60904-1-1 [4] and IEC 60904-8-1 [5] – were published with specific requirements for the measurement and the calibration of MJ PV devices for terrestrial applications. All the prerequisites set by the other parts of the IEC 60904 series of standards apply to MJ PV as well, unless they are specifically amended by these two documents. IEC 60904-1-1 deals with the measurement and the calibration of the current-voltage characteristics (I-V curve) of MJ PV devices; IEC 60904-8-1 covers the measurement and the calibration of their SR.

Due to the prevalence of SJ PV technologies in terrestrial PV applications, the use of specific procedures for the measurement and calibration of MJ PV devices is not as diffused in the terrestrial PV community as it is in the space PV community. However, the specific requirements contained in these two standards are essential to achieve a reliable assessment of the MJ PV performance with a reasonable uncertainty. Among them, the use of a junction-specific bias light as well as of a bias voltage during the measurement and the calibration of the SR of MJ PV devices is crucial.

([10]) Direct sunlight method (DSM), global sunlight method (GSM) and solar simulator method (SSM) from IEC 60904-4 [8].
([11]) Typically up to 1800 nm, contrarily to typical upper limit of SJ PV at 1200 nm or lower.

2.2.3 IEC 60904-9

This standard deals with the characterisation and consequent classification of the solar simulators that are used for measurement and calibration of PV devices, both in space and in terrestrial applications. The new edition was recently published after an intense revision process [6].

In the latest edition, a clear remark on the importance of a regular characterisation of the solar simulators was introduced, as their performance and therefore their classification is usually not steady during their operational life. Factors like:

— elements influencing the direct beam and/or the stray light, such as optical filters or (spectrally-selective) reflecting elements,

— a change in the optical properties and/or in the positioning of the elements mentioned above,

— a change in the electrical power to the lamps or even simply their aging,

— the duration and the shape of the light's pulse,

— the presence and the correct performance of a feedback monitor device,

— any replacement of the lamps,

— the actual use of the solar simulator,

can modify the performance of a solar simulator and consequently its classification according to the criteria specified by IEC 60904-9 [6]. Therefore, the classification of the solar simulator in use should be periodically reviewed by the personnel at each laboratory, with the aim of restoring the original state whenever necessary and by means of appropriate solutions.

The main technical changes compared to the previous edition include:

4. the extension of the classification levels to include a new category A+. The latter aims in particular at high-accuracy calibration measurements and is less relevant for usual verifications in PV production lines;
5. the extension of the spectral range over which the solar simulators have to be classified, which now covers the wavelength band from 300 nm to 1200 nm ([12]) against the previous required range from 400 nm to 1100 nm;
6. the increase in the minimum set of measurements to check the uniformity of the spectral irradiance over the test plane;
7. the definition of two new quality indicators to classify the deviation of the spectral irradiance of the solar simulator from the reference spectrum AM1.5 [9];
8. the improvement of the measurement procedure to characterise the spatial non-uniformity of the irradiance, with particular emphasis on the detection of localised variations of the irradiance. The latter could indeed affect the PV measurement because of the difference in size between the monitor device or the reference device, which are used to set the irradiance level, and the device under test;
9. a clarification on the relevance boundaries of the irradiance's short-term and long-term instabilities.

2.2.4 Workshop's conclusions on standardisation activity

The presentations and the following discussion made clearer, if ever necessary, that adequate standardisation is fundamental for both terrestrial and space PV communities. Standardisation should cover a wide range of activities, from full calibrations to production's comparative measurements, with appropriate requirements. Some of the

([12]) This is the spectral range over which c-Si responds.

latter are shared by the two PV communities, because some of the standards developed at the IEC TC82 for the assessment of terrestrial PV ([13]) are also referred to and utilised by the space PV community, with proper amendments whenever necessary.

The standardisation work, carried out by each of the two PV communities inside their own standardisation organisation, should therefore foster deeper collaboration and constant reciprocal exchange between them from the first phases of the development of international standards for which a mutual interest exists, at least as much as this would be practical and appropriate. This exchange was already started several years ago, but the on-going or the future revision of some common standards should be the occasion to strengthen it even more.

From the presentations and the following discussion, it emerged that each PV community has specific boundaries to define standard requirements and methods for the assessment of PV performance and reliability. Those boundaries are mainly connected to the actual way in which PV is employed in the final application – either in space or on ground – and to the specific environmental conditions under which PV operates at its destination. As such, those boundaries cannot and should not be ignored when developing or revising the necessary international standards for PV. In the following, a summary of the conclusions on the main standardisation topics is given.

2.2.4.1 The reference spectral irradiances

PV for space is operated under a spectral irradiance that is defined by the AM0 spectrum. The latter, to be updated in the ISO 15387, is the result of statistical and metrological analysis of an ample amount of experimental data collected by spectroradiometers positioned outside the atmosphere. The aim of this data processing is to achieve a representative solar spectrum to be used as stable spectral reference for prediction and assessment of space PV performance.

Analogously, the AM1.5 reference spectrum for terrestrial PV is a conventional estimate of the natural sunlight that, on average, reaches the ground after crossing the terrestrial atmosphere under specific physical conditions. Such an estimate is based on a complex physical model, which modifies the extra-terrestrial AM0 spectrum by applying a long list of atmospheric and other physical parameters, so that the resulting output spectral distribution can be taken as representative of the terrestrial sunlight spectrum for terrestrial PV assessment. The model for the calculation of the AM1.5 reference spectrum, as tabulated in the IEC 60904-3 [9], is currently based on the estimate of the AM0 spectrum made in 2004 [10].

A future change in the AM0 spectrum and in its overall integral value, i.e. the TSI value, could in principle affect the spectral distribution – and to a smaller extent the absolute value – of the irradiance for terrestrial PV, too. However, the recent few-years discussion between the space and terrestrial PV communities on this very point brought to the conclusion that a change in the AM1.5 reference spectrum is not deemed neither necessary nor desired for the time being. This was reconfirmed at this workshop. This conclusion comes from the fact that, although based on representative physical quantities, the integral of the AM1.5 reference spectrum ([14]) is mainly used as conventional reference condition to compare terrestrial PV technologies. The modifications to the individual spectral components caused by the AM0 revision are also deemed not as much significant to revise the terrestrial reference spectrum at the present time.

2.2.4.2 The methods for PV primary calibration

The calibration of primary references is typically made in relation to standard test conditions, which consist in:

([13]) In particular, the IEC 60904 series of standards and the IEC 60891.
([14]) which equals 1000 W/m^2 of total irradiance.

— a TSI value equal to 1361.1 W/m^2 ([15]), the AM0 reference spectrum (see 2.2.1) and 25 °C of junction temperature for space PV [2];

— a conventional total irradiance of 1000 W/m^2, the AM1.5 reference spectrum and 25 °C of junction temperature for terrestrial PV [11].

As the reference spectrum for space PV is AM0 and this cannot reach the Earth's ground because of atmospheric absorptions, PV primary calibrations for space applications have to be performed at high altitude, either on balloons or on special high-altitude flights. The current edition of the ISO 15387 includes terrestrial methods, too, but the PV space community is considering to remove them from the next edition because of unacceptably large uncertainty in the calibration of PV cells, due to their larger spectral mismatch correction when the reference spectrum is AM0. The only other method that should be preserved for the primary calibration of PV for space is the DSR method.

Terrestrial PV uses the AM1.5 reference spectrum [9], which can be approximated very well by the natural sunlight's spectrum at ground under some conditions of clear sky. As a consequence, primary calibration methods for terrestrial PV include methods under natural sunlight, with spectral mismatch correction when necessary, as well as indoors methods, such as at solar simulators, besides the DSR method.

2.2.4.3 The standards IEC 60904-1-1 and IEC 60904-8-1 for MJ PV testing and calibration

The standards IEC 60904-1-1 [4] and IEC 60904-8-1 [5] are common subject to both space and terrestrial PV communities. They should indeed become normatively referred to by the next edition of the ISO 15387, even though they could be adjusted inside ISO 15387 to give specific requirements for PV for space applications. Consequently, members of the space PV community should be involved, at least in the role of observers, in the IEC normal standardisation works involving these two standards. An even more active participation of space PV members in the IEC works can be achieved by their official enrolment in the IEC National Committee either of their member state of origin or of their member state of employment, whenever these two do not coincide.

2.2.4.4 Classification of solar simulators

Solar simulators are used by both PV communities to test and calibrate PV cells and modules in all those circumstances where it is not possible to use the natural sunlight, either at high altitude or at ground. Although solar simulators can be provided with more than one light source to facilitate the adjustment of their spectral distribution to the reference spectrum, there is always a deviation between these two. The IEC 60904-9 sets the requirements for checking whether this deviation is within specific limits of acceptance. The latest edition of the standard (Ed. 3, 2020) classifies the solar simulators in four classes according to their spectral performance, whose assessment has also been extended to cover the entire range of the SR of c-Si. IEC 60904-9 Ed. 3 also introduces two additional quality indicators for the spectral classification of the solar simulators, i.e. the spectral deviation (SPD) and the spectral coverage (SPC). They help to verify whether the solar simulator's spectral distribution matches the reference spectrum and how well it covers the entire spectral range of interest.

The previous criteria for the spectral classification of solar simulators had become a topic of increasing debate inside both PV communities. Those criteria could have still been sufficient for production quality checks of c-Si PV modules, but they were increasingly considered inadequate to ensure an acceptable uncertainty in testing other PV technologies, in particular MJ PV. As regards PV calibration, the normal practice of calibration laboratories was already to check and to adjust the spectral mismatch of the solar simulators well beyond the previous requirements by IEC 60904-9 Ed. 2. Finally, as extensive user and developer of MJ PV cells with an increasing number of junctions, the

([15]) This value considers the 2018's calculations by Gueymard, accepted by the scientific community.

space PV community was arguing whether the focus on the assessment of the solar simulators should be pointed on reducing the spectral mismatch in relation to the actual PV devices to be tested rather than on an absolute classification of the spectral distribution per se in relation to the reference spectrum. The new criteria adopted in the IEC 60904-9 Ed. 3, in particular the SPD and SPC indicators, go in this direction and should help both PV communities to become fully aware of the importance of a correct spectral match check for each measurement.

2.3 Characterisation session

The characterisation session focused on some topics of common interest that are currently under the spotlight of both space and terrestrial PV communities:

1. the PV traceability chain of solar irradiance measurements;
2. the good practices for PV measurement, with particular attention to MJ PV devices;
3. the explicit definition of spectrally-matched reference cells, which at present is missing in any published international standard;
4. the spectral irradiance measurements and spectral mismatch issues under simulated and natural sunlight, the latter to be meant as either terrestrial (AM1.5) or extra-terrestrial (AM0) solar spectrum depending on the PV community addressed;
5. the advanced characterisation methods for PV devices by means of:
   (a) angular SR (ASR) or angular integral responsivity measurements;
   (b) performance measurements at non-standard conditions of irradiance and/or temperature.

For all these subjects, a collaboration between the two communities could bring benefits to both of them by helping the improvement of measurement practices or the exchange of technical solutions to address common challenges in measurement or performance of PV devices.

2.3.1 Workshop's conclusions on characterisation activities

PV testing and calibration resulted to be the field where most of the collaboration and exchanges could take place between the two PV communities, with benefits for both of them in terms of know-how and mutual support. Also, it is clearly of utmost importance for all testing and calibration laboratories to regularly compare themselves with peers and to maintain the PV traceability chain uninterrupted, regardless of whether PV is for space or ground. Therefore, comparison campaigns on common measurement practices may be fruitfully enlarged to include laboratories from both communities.

In relation to the five points mentioned above, the following discussions took place with some conclusions and recommendations for further collaborations between the two communities.

2.3.1.1 Traceability chain for PV

The traceability chain is maintained by each PV community in part independently, because the reference spectral irradiance is not shared between them. However, the World Photovoltaic Scale (WPVS) adopted by the terrestrial PV community, and in particular systematically implemented at JRC-ESTI through the ESTI reference cells set [12], could become the subject of intense collaborative work between space and terrestrial PV. Indeed, the same approach is certainly applicable to c-Si PV reference cells for space applications and can be maintained independently by the PV space community. However, it could also be extended to other PV technologies both in terrestrial and in space PV, thus enlarging the availability of validated measurement data on reference cells that are calibrated by common methods. This would ultimately increase the confidence in the PV performance assessment, by also decreasing the uncertainty of those calibration values. Finally, even though the ESTI reference cell set that maintains the WPVS consists of c-Si reference cells only [12], its traceability chain can be and is transferred to other PV technologies by means of appropriate corrections (mainly for spectral mismatch).

2.3.1.2 MJ PV measurements

Although the space PV community has advanced faster than the terrestrial one in the adoption of MJ PV technologies, both communities are developing proper and eventually standardised testing and calibration procedures to assess MJ PV performance. The IEC TC82 working group 2 was indeed the first team to standardise specific requirements and measurement practices for MJ PV. Still, terrestrial PV is mainly focused on SJ PV technologies, with the exception of CPV, which is subject of the IEC TC82 working group 7. CPV has focused on MJ PV technologies because of their better response to the high heat loads due to the high energy densities involved. Therefore, support from the IEC TC82 working group 7 to the space PV community should be encouraged, too.

2.3.1.3 Definition of spectrally-matched reference cells

It is common practice in both terrestrial and space PV communities to identify a spectrally-matched reference cell with a PV cell that has SR nearly equal to the one of the PV device under test. This SR-matching criterion is crucial for indoor PV measurements at solar simulators, because it helps reducing the measurement uncertainty that is due to the spectral components, by minimizing the spectral mismatch and its correction [13, 14]. Although this is valid for all PV technologies, it is even more important for MJ PV testing and calibration [13, 14], because one of the junctions in the MJ PV stack limits the electrical current through the entire PV device under the actual spectral irradiance [15]. If the spectral irradiance changes, there can be even a swap of the junction that is limiting the PV device [16]. As the reporting of the PV performance is made at STC, it is important that the balance between the spectral bands of the solar simulator's irradiance is carefully adjusted to be consistent with the same balance that is present in the relevant reference spectrum, i.e. AM1.5 or AM0.

A proposal for a quantitative evaluation and consequent definition of a spectrally-matched PV reference cell was made during the workshop. It should be considered as input for the next revision of the IEC standards on MJ PV devices (see 2.2.2) or, possibly even better, for the next revision of the IEC 60904-2, which sets the requirements for PV reference devices [17].

2.3.1.4 Spectral irradiance measurements

Strictly connected to the adjustment of the spectral irradiance of the solar simulators and to the accurate evaluation and subsequent correction of the residual spectral mismatch in PV performance measurements, the measurement of the spectral distribution illuminating the device under test is crucial in both PV communities. It is also good practice in both PV communities to use spectrally-matched reference cells ([16]) as defined in 2.3.1.3 for the adjustment of the solar simulator's irradiance as well as for the PV performance measurements, in order to minimise the spectral mismatch correction. The latter has indeed always to be considered for any PV measurement, regardless of whether the PV device is SJ or MJ. In general, it is accepted by both PV communities that larger uncertainties have to be stated for a measurement result whenever such a spectral correction has not been applied as well as when a reference cell not perfectly matching the SR of the device under test has been used.

([16]) For MJ PV devices, these usually consist in a set of reference cells, each of which has either only one single junction or one active junction among a stack of multiple junctions that is spectrally matched to one of the junctions of the MJ PV device to be tested. These reference cells for MJ PV devices are usually referred to as component and isotype reference cells, respectively.

Since some years now, ESTI coordinates an international intercomparison on spectral radiometric measurements that involves participants from both terrestrial and space PV communities [18]. The recommendation is to maintain the periodical organisation of such a measurement intercomparison, because on the one side it supports the transfer of the PV radiometric traceability chain to the secondary laboratories through ESTI and, on the other side, it helps building and sharing good measurement practices in PV radiometry between the participant laboratories.

2.3.1.5 PV advanced characterisation: angle-of-incidence responsivity

Both space and terrestrial PV are subjected to be operated under light beam's angles of incidence that are different from the normal incidence at 90°, which is assumed on the contrary for the reference spectrum.

For terrestrial PV, this occurs ordinarily through the day and through the year because of the varying position of the sun in the sky and because of the meteorological conditions, which both affect the ratio between the direct beam and the diffused scattered light from the sky. For instance, under clear-sky conditions at midday about 85% of the irradiance comes from about 0.5° around the sun disk's position, but this percentage decreases to a much lower value under cloudy sky. In addition, even under clear sky, only PV modules mounted on a double-axis solar tracker would be able to maintain the same angle of incidence towards the sun for the whole daytime, while fixed PV installations are still exposed to the variation of the position of the sun during the day. Besides, the surrounding environment can also be source of diffused and reflected irradiance (i.e. albedo components) that reaches the PV module at angle of incidence other than 90°.

For space PV, on the contrary, the direct beam coming from the Sun determines the angle of incidence to the PV front surface. Still, a change in the angle of incidence may become essential to limit the exposure of the PV arrays to large thermal loads (see 2.1.3). When needed, the PV arrays are therefore reoriented from the 90° incidence to decrease the temperature of the PV cells. However, even though the cells for PV applications are not encapsulated, thus reducing the number of layers that can alter the effective irradiance reaching the active materials, the optical properties of the interface between the first layer of the PV cell and the empty space determine the amount of effective irradiance that enters the PV cell.

As a general rule valid for both terrestrial and space contexts, angles of incidence different from 90° diminish the amount of electromagnetic radiation that can cross the interface between materials with different physical properties, in this case optical properties. Often, the variation in the transmitted electromagnetic radiation is also wavelength dependent. The correct measurement of the angular responsivity of a PV device is thus one essential element that has to be considered in the evaluation of the annual energy yield of terrestrial PV modules [19, 20]. It is equally important, though, for the correct assessment of space PVAs' performance, especially when it comes to evaluate the available power to operate the spacecraft's systems under a range of different conditions. This topic is therefore one where a larger collaboration between space and terrestrial PV communities could be beneficial to both of them.

2.3.1.6 PV advanced characterisation: non-standard conditions

Standard test conditions for PV testing and calibration are defined for space as well as for terrestrial applications (see 2.2.4.2). They are the test conditions at which the PV performance is usually reported. However, as also mentioned in 2.3.1.5, the irradiance can vary because of variable environmental conditions or because of direct intervention on the PV assembly. Moreover, both on ground and in space, the temperature to which the PV devices are exposed can also vary inside a wide range, partly in connection to the irradiance that hits the devices.

For terrestrial PV, the irradiance range considered relevant is comprised between 100 W/m^2 and 1100 W/m^2, with a device temperature range from 15 °C to 75 °C. These conditions have been included in the IEC 61853 series of standards dealing with the energy rating of the terrestrial PV modules [21]. Although they represent the large majority of temperature and irradiance conditions to which terrestrial PV modules can be exposed, they do not cover all. For instance, PV modules attached or integrated into buildings can reach temperatures well above the upper limit of 75 °C, if there is not enough ventilation around them or when they are installed in hot climates.

For space PV, the temperatures can easily vary on an even wider range (see 2.1.2), depending on the exposure of the PVAs to the sunlight and on the distance of the spacecraft from the Sun. Both of these also imply a variation in the total irradiance that can reach the PVAs. Finally, as mentioned above, there is the possibility of controlling the irradiance by controlling the orientation of the PV arrays in relation to the direct beam, which further changes the total irradiance on the PVAs.

Both PV communities have developed and are refining measurement practices to vary the irradiance level in a controlled way during the performance tests in the laboratory. For terrestrial PV applications, this is standardised in IEC 60904-10 [22] and in IEC 61853-1 [21]. For space PV applications, it is not yet standardised in a document, but it follows a similar approach. In particular, some measurement challenges that arise at low irradiance levels were encountered and reported by both PV communities. Therefore, there seems to be a large common ground to strengthen the collaboration and the know-how exchange between the two PV communities on this topic, too.

3 Conclusions

The JRC-ESA joint workshop on “Advanced PV Measurements and Reliability” covered three activity areas, in order to identify the specific topics where collaboration between terrestrial and space PV communities might or would need to be strengthened. These areas are the reliability of PV devices; the standardisation activity in relation to their performance and reliability assessment; the state-of-the-art measurement best practices and their present or foreseeable future challenges for each PV community.

From the presentations given during the workshop and from the discussions held in connection to each area, the following outcomes can be summarised:

1. The historical aim at sharing advanced stress tests’ capabilities and practices does not find a reasonable practical solution, because the environmental conditions and the performance constraints to which the PV assemblies are subjected over their lifetime are rather different in terrestrial and in space applications. Consequently, the experimental approach does necessarily remain largely independent for each PV community, although a mutual exchange of know-how can be foreseen whenever shared standards are developed or revised.

2. On the contrary, a more intense collaboration on the reliability of PV devices could be developed in the modelling of the necessary thermal cycles or of proper solutions to mitigate the electrical mismatch of PV cells and their assemblies, with relation to the foreseeable operational conditions.

3. The area on standardisation is for a large part common to both PV communities. Stronger connection between them should be encouraged, including more frequent mutual consultation on common topics and more active participation of space PV community’s members in the terrestrial PV community’s standardisation activity and vice versa.

4. The area on PV device characterisation is the one where the two communities have the largest opportunity to collaborate and exchange good practices. Several topics that are currently at the core of experimental and standardisation activities in both PV communities were covered as well in this workshop. These include:

    (a) the maintenance of a reliable and uninterrupted PV traceability chain;

    (b) some challenges and gaps in relation to spectral aspects of the PV measurements. They are particularly important when dealing with MJ PV cells and modules, but they should not be ignored for SJ PV measurements, too;

    (c) advanced characterisation of PV devices beyond standard test conditions, such as spectral and total responsivity of PV cells and their assemblies at variable angle of incidence, as well as measurements at non-standard temperature and irradiance.

The concluding recommendation is therefore to maintain and reinforce the dialogue and the mutual beneficial exchange that have been established between the European terrestrial and space PV communities.

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List of abbreviations and definitions

AM0	Air-mass zero (where zero stands for the equivalent perpendicular column of atmosphere at the point where the spectrum is measured)
AM1.5	Air-mass 1.5 (where 1.5 stands for the equivalent perpendicular column of atmosphere at the point where the spectrum is measured)
ASR	Angular spectral responsivity
CPV	Concentrating PV
DSR	Differential spectral responsivity
ECSS	European Cooperation for Space Standardisation
ESA	European Space Agency
ESTEC	European Space Technology and Research Centre
ESTI	European Solar Test Installation
IEC	International Electrotechnical Commission
ISO	International Standardisation Organisation
JRC	Joint Research Centre
MJ	Multi-junction
PV	Photovoltaics
PVA	PV assembly
SJ	Single-junction
SPC	Spectral coverage
SPD	Spectral deviation
SR	Spectral responsivity
TC	Technical committee
TSI	Total solar irradiance

Annexes

Annex 1. Agenda of the JRC-ESA workshop on "Advanced PV Measurements and Reliability"

11th-12th November 2020 – ONLINE MEETING

Day 1

Session	Topics	Organisation	Presenter	Time schedule	
Welcome		JRC	Christian Thiel	14:00	14:05
Technical introduction		JRC - ESA	Elena Salis – Emilio Fernandez Lisbona	14:05	14:15
reliability/long-term resistance	Space cells accelerated aging test at very high temperatures for the determination of the activation energy	UPM	Carlos Algora	14:15	14:40
	Thermal cycling and humidity test on space solar arrays	ESA-ESTEC	Emilio Fernandez Lisbona	14:40	15:05
	Thermo-mechanical induced failures: Temperature cycle, thermal decomposition vs mechanical loading	Fraunhofer - CSP	Bengt Jäkel	15:05	15:30
	break			15:30	15:45
	Cell's mismatch and partial shadowing on space solar arrays	ESA-ESTEC	José Ramon Gonzalez	15:45	16:05

	Optimum PV module interconnection design and mounting orientation to reduce mismatch losses due to inhomogeneous soiling in desert regions	Fraunhofer - CSP	Hamed Hanifi	16:05	16:25
	Reliability overall discussion (moderator: T. Sample)			16:25	17:00

Day 2

Session	**Topics**	**Organisation**	**Presenter**	**Time schedule**	
Introduction 2nd day		JRC	Elena Salis	9:00	9:05
Standardisation	IS 15387 - Calibration procedures for space solar cells in view of a revised AM0 reference spectrum	ESA-ESTEC	Carsten Baur	9:05	9:30
	The standards for terrestrial multi-junction PV testing: IEC 60904-1-1 and IEC 60904-8-1	JRC-ESTI	Elena Salis	9:30	10:00
	New IEC 60904-9 Ed. 3 for solar simulator classification – Major changes and significance for PV power measurement	TÜV Rheinland	Werner Herrmann	10:00	10:30
	Standardisation overall discussion (moderator: H. Müllejans/T. Sample)			10:30	11:15
break				11:15	11:30

Session	Topics	Organisation	Presenter	Time schedule	
Characterisation (morning session)	Traceability and uncertainty of solar irradiance measurement in the context of the WPVS	JRC-ESTI	Harald Müllejans	11:30	12:00
	White paper on measurement and characterization techniques for multi-junction solar cells for space applications	ESA-ESTEC	Carsten Baur	12:00	12:25
	Quantitative assessment of spectrally-matched cells	INTA-Spasolab	Ana Gras	12:25	12:45
	Measuring solar simulators spectra at ESTI	JRC-ESTI	Diego Pavanello	12:45	13:00
Lunch break				13:00	14:00
Characterisation (afternoon session)	Low intensity measurements at large scale level, from room to low temperatures	Leonardo	Stefano Riva	14:00	14:25
	Characterization of concentrating and non-concentrating terrestrial PV using multi-junction cells	Fraunhofer - ISE	Gerald Siefer	14:25	14:45
	Solar Simulators for Multi-junction Solar Cells	Airbus	Andreas Gerhard	14:45	15:05
	Multi-junction PV calibration at ESTI	JRC-ESTI	Elena Salis	15:05	15:25
	break			15:25	15:40

Session	Topics	Organisation	Presenter	Time schedule	
	Spectral Angular Responsivity Calibration Facility at PTB - Investigating spectral effects for AOI measurement of PV devices	PTB	Ingo Kröger	15:40	15:55
	Angular response measurement of full-size PV modules with solar simulators	TÜV Rheinland	Werner Herrmann	15:55	16:10
	A comparative study of the angular performance behaviour of GaInP/GaAs/Ge triple-junction solar cells covered with conductive and non-conductive cover-glasses for deep space missions	Airbus	Seonyong Park	16:10	16:25
	Characterisation overall discussion (moderators: T. Sample/E. Fernandez Lisbona)			16:25	17:10

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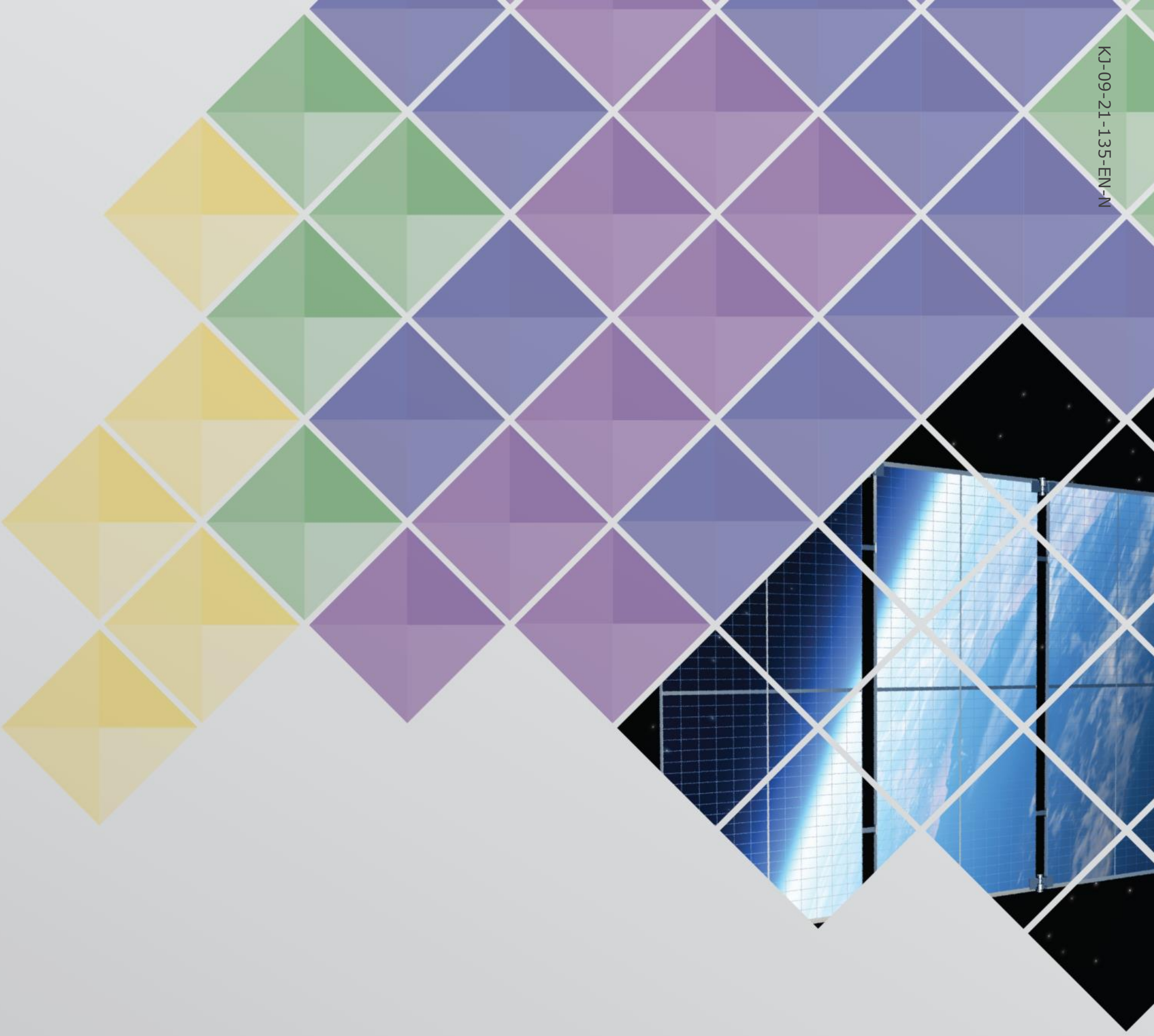

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