

High Specific Impulse Solutions for Orbit Raising, Orbit Topping and Station Keeping with the HEMP-T Electric Propulsion System

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Abstract: The increased demand for all-electric satellites changes the requirements of current electric propulsion systems (EPS), such that on the one hand high thrust at maximum available power is provided during orbit raising to minimize transfer time and radiation exposure and on the other hand high specific impulse is available for payload maximization during the station keeping phase. These different modes of operation are mutually exclusive: none of the current commercially available EPS can provide these two modes with only one type of thruster. The flexibility and long life of the HEMP-T make it the ideal basis for an EPS capable of operating at both these modes with the same thruster. The HEMP-T is capable of this due to the possibility of operating the HEMP-T anywhere between 500V and 1kV with a throttleability of the anode power from 500W up to 3kW. The HEMP-T based EPS is currently under qualification for the SGEO HAG1 mission in course of the HEMPTIS in orbit verification program. Only minor modifications to the current hardware, in order to allow increased power throughput, will be necessary such that effort and time for a delta-qualification is minimized. Additionally a clustering of the modified thruster increases reliability and lowers cost.

Nomenclature

SGEO HAG1 = Small GEO Hispasat AG1
HEMP-T = High Efficiency Multistage Plasma Thruster

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<i>HEMPTIS</i>	=	HEMP-T In orbit verification on SGEO
<i>HTM</i>	=	HEMP-Thruster Module
<i>HTA</i>	=	HEMP-Thruster Assembly
<i>FCU</i>	=	Flow Control Unit
<i>PSCU</i>	=	Power Supply and Control Unit
<i>PID</i>	=	Proportional, Integral and Derivative
<i>ICAU</i>	=	
<i>EOL</i>	=	X component of the resultant pressure force acting on the vehicle
<i>EP</i>	=	Y component of the resultant pressure force acting on the vehicle
<i>EPS</i>	=	generic functions
<i>PTTR</i>	=	height
<i>Isp</i>	=	time index during navigation
<i>j</i>	=	waypoint index
<i>K</i>	=	trailing-edge (TE) non-dimensional angular deflection rate

I. Introduction

THALES Electron Devices currently develops and qualifies a novel type of ion propulsion system based upon the High Efficiency Multistage Plasma Thruster HEMP-T. In course of the HEMPTIS project (HEMP-Thruster In Orbit Verification on SmallGEO) the German Space Agency (DLR) funds the development and qualification of this propulsion system for the SmallGEO HAG1 mission with the purpose of North/South and East/West station keeping.

Since the Announcement of Boeing in 2012 to having acquired a contract to build four all-electric satellites, the 702SP, and the European's reaction with Electra within the Artes 33 framework, there is an increased interest in electric propulsions systems (EPS) which are not only capable of station keeping but can also provide the transfer into geostationary orbit. Additionally the trend towards increased satellite launch mass calls for higher thrust and total impulse requirements. The simplicity, robustness and flexibility of the HEMP-T technology provides excellent adaptability and makes it an ideal thruster candidate as a basis for an electric propulsion system for these new demands with minimal changes to the system and its qualification status.

This paper will describe the possibilities and advantages of an EPS for an all-electric satellite based upon the HEMP-Thruster. To achieve this, a description of the EPS components for HEMPTIS is provided first, after which the requirements for orbit raising/topping and station keeping are discussed. This results in the proposed EPS configuration based upon the HEMP-T, operated in two separate modes with each specific performance characteristics.

II. HEMP-T Qualification Hardware for SGEO HAG1

The HEMP Thruster Assembly (HTA) which is to be qualified in course of HEMPTIS comprises of one <power Supply and Control Unit (PSCU) and four HEMP Thruster Modules (HTM). Each HTM contains the following components: one HEMP-Thruster, one neutralizer HCN5000, one Flow Control Unit (FCU) and one electrical connector box, all mounted upon a single mechanical structure which acts as the thermal and mechanical interface to the satellite.

The HEMP-Thruster consists of a dielectric discharge channel surrounded by a permanent magnet system where the axially magnetized ring magnets are orientated in opposite direction: the PPM system. **REF PAPER NBOBERT** The downstream end is open whereas at the upstream end the anode is located. The anode assembly provides the acceleration voltage and acts as the propellant inlet. The magnetic topology of the PPM system causes a magnetically confined plasma to be generated within the discharge channel as soon the high voltage is applied and an ionizable gas is present within the discharge channel. One of the key characteristics of the HEMP-T is that no discharge or leak current will occur when the high voltage is applied to the anode, but no gas is present inside the discharge channel. This enables the configuration as used for SGEO HAG1, where all thrusters are connected to a common anode potential. In this case all thrusters are energized but do not draw power or produce thrust until gas is fed through the FCU into the thruster. This characteristic is especially useful in configurations where only one thruster is active at a time, such as is the case for an EPS for station keeping. From the point of thruster ignition the HEMP-Thruster exhibits a very smooth current ramp-up, this is due to the linear relation between the propellant influx, the anode current and the generated thrust. This means a very precise control of the thrust level is possible by control of the propellant flow. The HEMP-Thruster has already displayed a stable field of operation for a wide variety of anode potential **REF MARTIN** from 500 V up to 2000 V and anode currents from 0.3 A to 9 A. This

flexibility combined with an erosion-free discharge channel opens up a wide variety of applications for the HEMP-T.

The HCN5000 Neutralizer is based upon the extensive cathode flight experience of the Thales traveling wavetubes (TWT) with more than 500 million accumulated hours in space. The Thales Barium impregnated Tungsten-Osmium mixed-metal matrix life is mainly determined by the cathode temperature. REF MARTIN This dependency has been extensively researched for the TWT cathodes and a life prediction model was verified. REF LIFETIME The HCN5000 runs at temperatures well below 1000°C and has a life prediction of over 100 kilohours. REF The HCN5000 is capable of a nominal neutralization current of up to 5A. An important feature of the Thales cathode is that the keeper ignition voltage is around 17 Volts, such that no high voltage puls is required to ignite the keeper discharge and thus power supply complexity is reduced. Like any Barium impregnated hollow dispenser cathode also the Thales cathode is sensitive to humidity. For this reason an extensive storage qualification was successfully performed to ensure the life capability of the cathode even after exposure to air for extended periods of time during the MAIT phase and waiting time on the launch pad within the launcher fairing. Ref Kathoden paper

The FCU feeds xenon propellant to both the thruster and the neutralizer. The FCU inlet contains a five-micron inlet filter followed by an isolation valve, after which the massflow is separated into neutralizer and thruster feed lines, both limited by flow restrictors. The neutralizer line includes an exit isolation valve and a getter for oxygen, hydrocarbons and water, to prevent these contaminations from reacting with the hot cathode during operation. The thruster line is defined by a flow control valve instead of an isolation valve. The current to this proportional valve is supplied by the PSCU, through a PID controller in which the thruster current acts as the feedback signal; this is possible due to the linear proportionality of the anode current with respect to the propellant throughput. The advantage of the proportional valve is a very exact control over the thruster current and thus its thrust. Through this valve the FCU enables throttling capability of the thruster anode current and thus the thrust down to 20% of its nominal operational point.

The PSCU has a modular design and provides the low voltage power forms for up to four neutralizers and FCU's simultaneously, as well as the high voltage power form to all thrusters simultaneously, through the same anode line. The PSCU incorporates two high voltage modules, each capable of providing 1.4 kW. For SGE0 HAG1 the second module is used in cold redundancy, multiple thrusters could however be operated simultaneously, providing 2.8 KW to one thruster, or distributed over several thrusters. Distribution over several thrusters is possible through the Anode Current Measuring Unit (ACMU), which contains a sensing channel for each thruster. Control over thruster firing sequences, telemetry acquisition and failure handling is performed by the PSCU ICAU module, minimizing the efforts required on the spacecraft bus side. REF ASTRUM?

III. Orbit Raising, Orbit Topping and Station Keeping

Orbit raising and orbit topping are maneuvers to position a satellite in its final orbit, where orbit raising uses only EP from injection orbit to target orbit and orbit topping is performed by a combination of chemical propulsion and EP. Whereas these orbit maneuvers can be absolved within a few orbits by chemical propulsion, the application of EP and thus reduced thrust values by a few orders of magnitude brings one main restriction into focus: the transfer time. A longer transfer time has two effects: the longer a satellite takes to reach its final position the longer it takes for the operating company to reach its return of invest: depending on the injection orbit transfer times can take 60 to more than 100 days. Additionally, as long as a satellite is injected with the orbit perigeum below 10.000 km each orbit takes the satellite through the lower Van Allen Belts REF DUCHEMIN/SMARTI. This region, populated by high energetic protons, has a degrading effect on satellite electronics and reduces the power output of the solar arrays. For this reason the duration and orbits at these regions should be kept at a minimum. For the duration of the orbit transfer the full satellite electrical power is available to the EPS minus the power required for housekeeping, the logical conclusion is to maximize the thrust with respect to the available power und thus reduces the transfer time. The available power, dependent upon the satellite size, ranges from 5kW to more than 15kW. REF?

Station keeping, when compared to orbit raising or topping, is the opposite. Although a minimum thrust level is required to keep the maneuvers around the orbital nodes efficient, the available power is limited by the EOL available power and the power demand from the commercial payload, meaning a low power-to-thrust ratio (PTTR) would be beneficial. The total impulse requirement for station keeping is approximately equal to the amount needed for the orbit raising, the time factor however is no longer critical. For this reason increased propellant efficiency leads to increased mass for more transponders or reduced satellite wet mass. Increasing the anode potential for station keeping would increase the thruster's exhaust velocity and thus higher specific impulse (Isp) than a thruster for orbit raising. The downside is that both a low PTTR and high Isp are mutually exclusive, this is seen from combining eq.1 with eq.2 to form eq.3 and comparing this with eq.4.

$$\begin{aligned}
T &= \dot{m}_{prop} \cdot v \cdot \cos \alpha_{eff} \propto \sqrt{M_{prop}} \cdot I_{ion} \cdot \sqrt{U_{eff}} \cdot \cos \alpha_{eff} \\
P &= \frac{1}{2} \cdot \dot{m}_{prop} \cdot v^2 = \frac{T^2}{2 \cdot \dot{m}_{prop}} \propto M_{prop} \cdot I_{ion} \cdot U_{eff} \cdot \cos^2 \alpha_{eff} \\
PTTR &= \frac{P}{T} \propto \sqrt{\frac{U_{eff}}{M_{prop}}} \cdot \cos \alpha_{eff} \\
I_{sp} &= \frac{T}{\dot{m}_{prop} \cdot g} \propto \sqrt{U_{eff}} \cdot \cos \alpha_{eff}
\end{aligned}$$

In conclusion, an EPS used for both orbit raising, topping and station keeping is forced to comply with two different sets of performance requirements, for orbit raising high thrust performance is needed whereas for station keeping a high I_{sp} is desirable as long as the minimal thrust is guaranteed.

IV. The HEMP-T Solution for Orbital Maneuvers

The unique ability of the HEMP-T to perform in a wide operational range, with high thrust on the one hand and high I_{sp} on the other, makes it the ideal technology as a basis for the EPS to perform both the orbit raising maneuver as well as station keeping with the identical type of thruster. This approach removes the necessity for the expensive development of different types of thrusters, increases production volume and thus reduces costs.

Thales proposes an EPS based on the HEMP-Thruster, where multiple thrusters are clustered together for high power throughput. Mounting of such a HEMP-Thruster Cluster (HTC) on a Thruster Orientation Mechanism (TOM) would enable the system to perform both the orbit raising/topping as well as the consecutive station keeping in north/south and east/west direction, including momentum wheel offloading. Due to the absence of erosion of the HEMP-T discharge channel and the 8000h endurance test results on the HTM 3050, it is believed the amount of total impulse, depending on the satellite mass this ranges around 3MNs, can be provided by the thrusters of such a system.

A HTC comprises of at least 2 thrusters, where each thruster is powered by a single PSCU at an anode input power of up to 2.5kW. The neutralizers are positioned close to each other, in between the thrusters, to allow the option of cross-neutralization of one neutralizer with any other thruster. The thrusters are based upon the HEMP-T 3050, but modified in order that they are operated at an elevated thrust level. The modification involves an increase of the thruster radiator size, such that the magnet system is kept within the same thermal regime as it is the case for the SGEO HAG1 mission. Minor modifications to the FCU will result in a necessary increased propellant throughput while retaining the heritage design. The necessary changes are the flow resistance of the flow restrictors and the orifice size of the FCV. The current high voltage module of the PSCU will have to be adapted to accommodate at least two anode voltage setpoints as well as enable an increase of the available anode power. A consequence of the redesign is that only one high voltage module would be needed per PSCU, reducing complexity. The neutralizer would require no changes, since the neutralizer is designed for a 5A neutralization current.

The HTC would have at least two separate points of operation. For orbit raising/topping each thruster would provide a maximum thrust of 94mN at 2200s I_{sp} by operating at 2.5kW anode power at 500V, therefore a HTC with 2 thrusters would, including neutralizers and FCUs, provides 188mN of thrust at 2000s system I_{sp} at 5.6kW PSCU input power. The thrust and thus the input power can be stepless reduced in case less power is available on the spacecraft bus side. In case more thrust is necessary and more power available an HTC with 3 thrusters or 2 HTCs with 2 thrusters can be chosen. For station keeping at least 2 HTCs are required with a total of at least four thrusters. An even number of thruster has the advantage that thrusters can be assembled with opposite magnetic field orientation, thus the permanent magnets do not cause magnetic momentum upon the satellite. During station keeping a high I_{sp} is preferred over high thrust, therefore once the target orbit is reached the PSCU switches the output voltage to 1000V and drives the thrusters at their high I_{sp} operational point. In this case each thruster provides 76mN of thrust at 2900s I_{sp} with an anode power of 2.5kW. Only one thruster, neutralizer and FCU is operational per HTC, leaving the second set as cold redundancy, thus improving reliability. When a higher total thrust is required the second thruster can be operated, also at a reduced thrust level to better match the available power.

V. Conclusion

With the HTC Thales aims to provide a multi-use EPS for both orbit raising/topping and station keeping. Explain thrust and isp here

Both required functionalities of high thrust at moderate Isp or high Isp at moderate thrust are made available by the unique feature of the HEMP-T of stable operation through a variable anode voltage and power range. The high life prediction of the HEMP-T due to the erosion free discharge channel makes it possible to perform both types of maneuvers with the exact same thruster, thus negating the need for a second EPS or having to accept loss of time and/or mass efficiency.

Although a thermal redesign of the thruster, minor changes to the FCU and adaptation of the PSCU are required to enable the increased power output, most of the HEMP-T qualification for SGEO HAG1 will apply. Using the HEMP-T 3050 as the basis for the HTC and applying clustering instead of newly developing high power thrusters, combined with powering each thruster with a dedicated PSCU, severely reduces complexity, development time and cost, as well as increases production volume and reliability.

VI. Solution

thrusters Two different types of HTC options have been identified: a HTC with two thrusters (HTC 5015) and a HTC with three thrusters (HTC 7515),

Orbit raising / SK different operations: time vs isp. Thrust vs cycles

Prevent long ground qualification: 2 sets or both with 1! But long qualification

Proton fluence van allen belts

MNs for orbit raising/station keeping -> with reference

a low PTTR and high Isp are mutually exclusive + formula?

This propulsion system

All are conducted in course of the HEMPTIS Project (HEMP-Thruster

, with at least two operational points. The first operational point is at an anode voltage of 500 V for orbit raising/topping

and 1000 V for station keeping.

From a system point of view the point of operation of the thruster need to be provided by the PSCU. Therefore the necessity for a PSCU 500 + 1000

Advantage same thruster both application: no extra high power thruster, no extra qual. 1 thruster is long qual time downside. Switchable pscu

What change wrt hag1 hardware necessary? Fcu/thermal redesign/pscu

Hemp can do high lifetime at high thrust

Parameter feld + 500V+1000V 2.8 kW +bild

MNs raising/keeping

VII. General Guidelines

The styles and formats for the IEPC13 Template have been incorporated into the structure of this document. If you are using Microsoft Word 6.0 or later, please use this template to prepare your manuscript. A template for LaTeX is available separately. Please upload a PDF version of the final typeset manuscript.

A. Document Text

The default font for IEPC13 papers is Times New Roman, 10-point size. In the electronic template, use the “Text” style from the pull-down menu to format all primary text for your manuscript. The first line of every paragraph should be indented, and all lines should be single-spaced. Default margins are 1-inch (2.54 cm) on all sides. In the electronic version of this template, all margins and other formatting is preset. There should be no additional lines between paragraphs.

Extended quotes, such as this example, are to be used when material being cited is longer than a few sentences, or the standard quotation format is not practical. In this Word template, the appropriate style is “Extended Quote” from the drop-down menu. Extended quotes are to be in Times New Roman, 9-point font, indented 0.4” and full justified.

B. Headings

The title of your paper should be typed in bold, 18-point type, with capital and lower-case letters, and centered at the top of the page. As shown above, the words “IEPC-2013-xxx” should follow, where xxx is the submission number you received in the acceptance email message you received in July. The names of the authors, business or academic affiliation, city, and state/province should follow on separate lines below the title. The names of authors with the same affiliation can be listed on the same line above their collective affiliation information. Author names are centered, and affiliations are centered and in italic type. The affiliation line for each author is to include that author’s city, state, and zip/postal code (or city, province, zip/postal code and country, as appropriate). The first footnote (lower left-hand side) is to contain the job title and department name, and email address of each author.

Major headings (“Heading 1” in the template style list) are bold 11-point font, centered, and numbered with Roman numerals.

Subheadings (“Heading 2” in the template style list) are bold, flush left, and numbered with capital letters.

Sub-Subheadings (“Heading 3” in the template style list) are italic, flush left, and numbered (1. 2. 3. etc.)

C. Abstract

The abstract should appear at the beginning of your paper. It should be one paragraph long (not an introduction) and complete in itself (no reference numbers). It should indicate subjects dealt with in the paper and state the relevance and objectives of the investigation followed by an accurate but succinct summary of the results or findings. Newly observed facts and conclusions of the experiment or argument discussed in the paper must be stated in summary form; readers should not have to read the paper to understand the abstract. The abstract should be bold, indented 3 picas (1/2”) on each side, and separated from the rest of the document by two blank lines.

D. Footnotes and References

Footnotes, where they appear, should be placed above the 1-inch (2.54 cm) margin at the bottom of the page. To insert footnotes into the template, use the Insert>Footnote feature from the main menu as necessary. Footnotes are formatted automatically in the text, but if another medium is used, should appear in superscript as symbols in the sequence, *, †, ‡, §, ¶, #, **, ††, ‡‡, §§, etc.

List and number all bibliographical references at the end of the paper. Corresponding superscript numbers are used to cite references in the text,¹ unless the citation is an integral part of the sentence (e.g., “It is shown in Ref. 2 that...”) or follows a mathematical expression: “ $A^2 + B = C$ (Ref. 3).” For multiple citations, separate reference numbers with commas,^{4,5} or use a dash to show a range.⁶⁻⁸ Reference citations in the text should be in numerical order.

In the reference list, give all authors’ names; do not use “et al.” unless there are six authors or more. Papers that have not been published should be cited as “unpublished”; papers that have been submitted or accepted for publication should be cited as “submitted for publication.” Private communications and personal Web sites should appear as footnotes rather than in the reference list.

References should be cited according to the standard publication reference style (for examples, see the “References” section of this template). As a rule, all words are capitalized except for articles, conjunctions, and prepositions of four letters or fewer. Names and locations of publishers should be listed; month and year should be included for reports and papers. For papers published in translation journals, please give the English citation first, followed by the original foreign language citation.

E. Images, Figures, and Tables

All artwork, captions, figures, graphs, and tables will be reproduced in the IEPC13 proceedings exactly as submitted. Tables and figures of all types should be inserted into text boxes (or frames, if text boxes are not practical) as illustrated here. Text boxes should have no background and no outlines. Both the illustration itself and

the caption should be included in the same box. In the electronic template, use the “Figure” style from the pull-down formatting menu to type caption text. Captions are bold and justified, with a period and a single tab (no hyphen or other character) between the figure number and figure description.

Place figure captions below all figures; place table titles above the tables. If your figure has multiple parts, include the labels “a),” “b),” etc. below and to the left of each part, above the figure caption. Please verify that the figures and tables you mention in the text actually exist. *Please do not include captions as part of the figures, and do not put captions in separate text boxes linked to the figures.* When citing a figure in the text, use the abbreviation “Fig.” except at the beginning of a sentence. Do not abbreviate “Table.” Number each different type of illustration (i.e., figures, tables, images) sequentially with relation to other illustrations of the same type.

Figure axis labels are often a source of confusion. Use words rather than symbols. As in the example to the right, write the quantity “Magnetization” rather than just “M.” Do not enclose units in parenthesis, but rather separate them from the preceding text by commas. Do not label axes only with units. As in Fig. 1, for example, write “Magnetization, A/m” or “Magnetization, A · m⁻¹,” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature, K,” not “Temperature/K.”

Multipliers can be especially confusing. Write “Magnetization, kA/m” or “Magnetization, 10³ A/m.” Do not write “Magnetization (A/m) × 1000” because the reader would not then know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels must be legible, approximately 8-12 point type.

F. Equations, Numbers, Symbols, and Abbreviations

Equations are centered and numbered consecutively, with equation numbers in parentheses flush right, as in Eq. (1). Insert a blank line on either side of the equation. First use the equation editor to create the equation. If you are using Microsoft Word, use either the Microsoft Equation Editor or the MathType add-on (<http://www.mathtype.com>) for equations in your paper, use the function (Insert>Object>Create New>Microsoft Equation or MathType Equation) to insert it into the document. Please note that “Float over text” should *not* be selected. To insert the equation into the document:

- 1) Select the “Equation” style from the pull-down formatting menu and hit “tab” once.
- 2) Insert the equation, hit “tab” again,
- 3) Enter the equation number in parentheses.

A sample equation is included here, formatted using the preceding instructions. To make your equation more compact, you can use the solidus (/), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators.

$$\int_0^{r_2} F(r, \varphi) dr d\varphi = [\sigma r_2 / (2\mu_0)] \cdot \int_0^\infty \exp(-\lambda |z_j - z_i|) \lambda^{-1} J_1(\lambda r_2) J_0(\lambda r_i) d\lambda \quad (1)$$

Be sure that the symbols in your equation are defined before the equation appears, or immediately following. Italicize symbols (*T* might refer to temperature, but *T* is the unit tesla). Refer to “Eq. (1),” not “(1)” or “equation (1)” except at the beginning of a sentence: “Equation (1) is...” Equations can be labeled other than “Eq.” should they represent inequalities, matrices, or boundary conditions. If what is represented is really more than one equation, the abbreviation “Eqs.” can be used.

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Very common abbreviations such as IEPC, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write “P.R.,” not “P. R.” Delete periods between

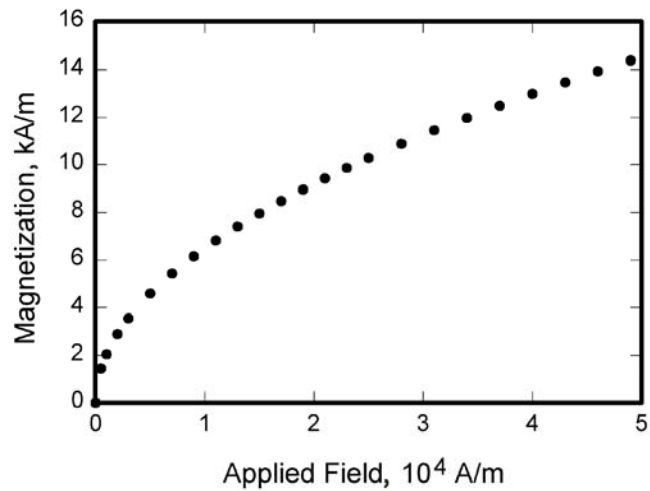


Figure 1. Magnetization as a function of applied field. *Figure captions should be bold and justified, with a period and a single tab (no hyphen or other character) between the figure number and the figure description.*

initials if the abbreviation has three or more initials; e.g., U.N. but ESA. Do not use abbreviations in the title unless they are unavoidable (for instance, “IEPC” in the title of this article).

G. General Grammar and Preferred Usage

Use only one space after periods or colons. Hyphenate complex modifiers: “zero-field-cooled magnetization.” Avoid dangling participles, such as, “Using Eq. (1), the potential was calculated.” [It is not clear who or what used Eq. (1).] Write instead “The potential was calculated using Eq. (1),” or “Using Eq. (1), we calculated the potential.”

Use a zero before decimal points: “0.25,” not “.25.” Use “cm²,” not “cc.” Indicate sample dimensions as “0.1 cm x 0.2 cm,” not “0.1 x 0.2 cm².” The preferred abbreviation for “seconds” is “s,” not “sec.” Do not mix complete spellings and abbreviations of units: use “Wb/m²” or “webers per square meter,” not “webers/m².” When expressing a range of values, write “7 to 9” or “7-9,” not “7~9.”

A parenthetical statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within parenthesis.) In American English, periods and commas are placed within quotation marks, like “this period.” Other punctuation is “outside”! Avoid contractions; for example, write “do not” instead of “don’t.” The serial comma is preferred: “A, B, and C” instead of “A, B and C.”

If you wish, you may write in the first person singular or plural and use the active voice (“I observed that...” or “We observed that...” instead of “It was observed that...”). Remember to check spelling. If your native language is not English, please ask a native English-speaking colleague to proofread your paper.

The word “data” is plural, not singular (i.e., “data are,” not “data is”). The subscript for the permeability of vacuum μ_0 is zero, not a lowercase letter “o.” The term for residual magnetization is “remanence”; the adjective is “remanent”; do not write “remnance” or “remnant.” The word “micrometer” is preferred over “micron” when spelling out this unit of measure. A graph within a graph is an “inset,” not an “insert.” The word “alternatively” is preferred to the word “alternately” (unless you really mean something that alternates). Use the word “whereas” instead of “while” (unless you are referring to simultaneous events). Do not use the word “essentially” to mean “approximately” or “effectively.” Do not use the word “issue” as a euphemism for “problem.” When compositions are not specified, separate chemical symbols by en-dashes; for example, “NiMn” indicates the intermetallic compound Ni_{0.5}Mn_{0.5} whereas “Ni–Mn” indicates an alloy of some composition Ni_xMn_{1-x}.

Be aware of the different meanings of the homophones “affect” (usually a verb) and “effect” (usually a noun), “complement” and “compliment,” “discreet” and “discrete,” “principal” (e.g., “principal investigator”) and “principle” (e.g., “principle of measurement”). Do not confuse “imply” and “infer.”

Prefixes such as “non,” “sub,” “micro,” “multi,” and “ultra” are not independent words; they should be joined to the words they modify, usually without a hyphen. There is no period after the “et” in the abbreviation “et al.” The abbreviation “i.e.,” means “that is,” and the abbreviation “e.g.,” means “for example” (these abbreviations are not italicized).

VIII. Conclusion

A conclusion section is not required, though it is preferred. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. *Note that the conclusion section is the last section of the paper that should be numbered. The appendix (if present), acknowledgment, and references should be listed without numbers.*

Appendix

An appendix, if needed, should appear before the acknowledgements.

Acknowledgments

The preferred spelling of the word “acknowledgment” in American English is without the “e” after the “g.” Avoid expressions such as “One of us (S.B.A.) would like to thank...” Instead, write “F. A. Author thanks...” *Sponsor and financial support acknowledgments are also to be listed in the “acknowledgments” section.*

References

The following pages are intended to provide examples of the different reference types. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

Periodicals

¹Vatistas, G. H., Lin, S., and Kwok, C. K., "Reverse Flow Radius in Vortex Chambers," *AIAA Journal*, Vol. 24, No. 11, 1986, pp. 1872, 1873.

²Dornheim, M. A., "Planetary Flight Surge Faces Budget Realities," *Aviation Week and Space Technology*, Vol. 145, No. 24, 9 Dec. 1996, pp. 44-46.

³Terster, W., "NASA Considers Switch to Delta 2," *Space News*, Vol. 8, No. 2, 13-19 Jan. 1997, pp., 1, 18.

All of the preceding information is required. The journal issue number ("No. 11" in Ref. 1) is preferred, but the month (Nov.) can be substituted if the issue number is not available. Use the complete date for daily and weekly publications. Transactions follow the same style as other journals; if punctuation is necessary, use a colon to separate the transactions title from the journal title.

Books

⁴Peyret, R., and Taylor, T. D., *Computational Methods in Fluid Flow*, 2nd ed., Springer-Verlag, New York, 1983, Chaps. 7, 14.

⁵Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

⁶Volpe, R., "Techniques for Collision Prevention, Impact Stability, and Force Control by Space Manipulators," *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1994, pp. 175-212.

Publisher, place, and date of publication are required for all books. No state or country is required for major cities: New York, London, Moscow, etc. A differentiation must always be made between Cambridge, MA, and Cambridge, England, UK. Note that series titles are in roman type.

Proceedings

⁷Thompson, C. M., "Spacecraft Thermal Control, Design, and Operation," *AIAA Guidance, Navigation, and Control Conference*, CP849, Vol. 1, AIAA, Washington, DC, 1989, pp. 103-115

⁸Chi, Y., (ed.), *Fluid Mechanics Proceedings*, SP-255, NASA, 1993.

⁹Morris, J. D. "Convective Heat Transfer in Radially Rotating Ducts," *Proceedings of the Annual Heat Transfer Conference*, edited by B. Corbell, Vol. 1, Inst. Of Mechanical Engineering, New York, 1992, pp. 227-234.

At a minimum, proceedings must have the same information as other book references: paper (chapter) and volume title, name and location of publisher, editor (if applicable), and pages or chapters cited. Do not include paper numbers in proceedings references, and delete the conference location so that it is not confused with the publisher's location (which is mandatory, except for government agencies). Frequently, CP or SP numbers (Conference Proceedings or Symposium Proceedings numbers) are also given. These elements are not necessary, but when provided, their places should be as shown in the preceding examples.

Reports, Theses, and Individual Papers

¹⁰Chapman, G. T., and Tobak, M., "Nonlinear Problems in Flight Dynamics," NASA TM-85940, 1984.

¹¹Steger, J. L., Jr., Nietubicz, C. J., and Heavey, J. E., "A General Curvilinear Grid Generation Program for Projectile Configurations," U.S. Army Ballistic Research Lab., Rept. ARBRL-MR03142, Aberdeen Proving Ground, MD, Oct. 1981.

¹²Tseng, K., "Nonlinear Green's Function Method for Transonic Potential Flow," Ph.D. Dissertation, Aeronautics and Astronautics Dept., Boston Univ., Cambridge, MA, 1983.

Government agency reports do not require locations. For reports such as NASA TM-85940, neither insert nor delete dashes; leave them as provided by the author. Place of publication *should* be given, although it is not mandatory, for military and company reports. Always include a city and state for universities. Papers need only the name of the sponsor; neither the sponsor's location nor the conference name and location are required. *Do not confuse proceedings references with conference papers.*

Electronic Publications

CD-ROM publications and regularly issued, dated electronic journals are permitted as references. Archived data sets also may be referenced as long as the material is openly accessible and the repository is committed to archiving the data indefinitely. References to electronic data available only from personal Web sites or commercial, academic, or government ones where there is no commitment to archiving the data are not permitted (see Private Communications and Web sites).

¹³Richard, J. C., and Fralick, G. C., "Use of Drag Probe in Supersonic Flow," *AIAA Meeting Papers on Disc* [CD-ROM], Vol. 1, No. 2, AIAA, Reston, VA, 1996.

¹⁴Atkins, C. P., and Scantelbury, J. D., "The Activity Coefficient of Sodium Chloride in a Simulated Pore Solution Environment," *Journal of Corrosion Science and Engineering* [online journal], Vol. 1, No. 1, Paper 2, URL: <http://www.cp.umist.ac.uk/JCSE/vol1/vol1.html> [cited 13 April 1998].

¹⁵Vickers, A., "10-110 mm/hr Hypodermic Gravity Design A," *Rainfall Simulation Database* [online database], URL: <http://www.geog.le.ac.uk/bgrg/lab.htm> [cited 15 March 1998].

Always include the citation date for online references. Break Web site addresses after punctuation, and do not hyphenate at line breaks.

Computer Software

¹⁶TAPP, Thermochemical and Physical Properties, Software Package, Ver. 1.0, E. S. Microware, Hamilton, OH, 1992.

Include a version number and the company name and location of software packages.

Patents

Patents appear infrequently. Be sure to include the patent number and date.

¹⁷Scherrer, R., Overholster, D., and Watson, K., Lockheed Corp., Burbank, CA, U.S. Patent Application for a “Vehicle,” Docket No. P-01-1532, filed 11 Feb. 1979.

Private Communications and Web Sites

References to private communications and personal Web site addresses are generally not permitted. Private communications can be defined as privately held unpublished letters or notes or conversations between an author and one or more individuals. They *may* be cited as references in some case studies, if absolutely necessary. Depending on the circumstances, private communications and Web site addresses may be incorporated into the main text of a manuscript or may appear in footnotes.

Unpublished Papers and Books

Unpublished works can be used as references as long as they are being considered for publication or can be located by the reader (such as papers that are part of an archival collection). If a journal paper or a book is being considered for publication choose the format that reflects the status of the work (depending upon whether it has been accepted for publication):

¹⁸Doe, J., “Title of Paper,” *Name of Journal* (to be published).

¹⁹Doe, J., “Title of Chapter,” *Name of Book*, edited by... Publisher’s name and location (to be published).

²⁰Doe, J., “Title of Work,” Name of Archive, Univ. (or organization) Name, City, State, Year (unpublished).

Unpublished works in an archive *must* include the name of the archive and the name and location of the university or other organization where the archive is held. Also include any cataloging information that may be provided. Always query for an update if a work is about to be published.