

**NAVAL**

**POSTGRADUATE**

**SCHOOL**

**MONTEREY, CALIFORNIA**

**THESIS**

**DEVELOPMENT OF INFORMATION ASSURANCE PROTOCOL FOR LOW BANDWIDTH NANOSATELLITE COMMUNICATIONS**

by

Cervando A. Banuelos II

**September 2017**

Thesis Advisor: Marcus Stefanou

Co-Advisor: Jim Horning

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| **1. AGENCY USE ONLY *(Leave blank)*** | | **2. REPORT DATE**  September 2017 | | **3. REPORT TYPE AND DATES COVERED**  Master’s thesis | | |
| **4. TITLE AND SUBTITLE**  DEVELOPMENT OF INFORMATION ASSURANCE PROTOCOL FOR LOW BANDWIDTH NANOSATELLITE COMMUNICATIONS | | | | | **5. FUNDING NUMBERS** | |
| **6. AUTHOR(S)** Cervando A. Banuelos II | | | | |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**  Naval Postgraduate School  Monterey, CA 93943-5000 | | | | | **8. PERFORMING ORGANIZATION REPORT NUMBER** | |
| **9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)**  N/A | | | | | **10. SPONSORING / MONITORING AGENCY REPORT NUMBER** | |
| **11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number \_\_\_\_N/A\_\_\_\_. | | | | | | |
| **12a. DISTRIBUTION / AVAILABILITY STATEMENT**  Approved for public release;Distribution is unlimited. | | | | | **12b. DISTRIBUTION CODE** | |
| **13. ABSTRACT (maximum 200 words)**  Nanosatellites provide a light, efficient, and cost effective way for research institutions to carry out experiments in low Earth orbit. These satellites frequently use the ultra-high and very high frequency bands to transfer their data to the ground stations, and oftentimes will use the internet protocol and the Transmission Control Protocol as a standard for communication to ensure the arrival and integrity of the data transmitted. Due to bandwidth limitations and signal noise, these connection-based protocols end up accruing a large data bandwidth cost in headers and retransmission costs. Furthermore, due to connection unreliability, encryption and integrity checks present a challenge.  The aim of this thesis was to develop a software based low-bandwidth reliable network protocol that can support a cryptographic system for encrypted communications using commercial off-the-shelf components. This protocol would reduce the data overhead, retain the retransmission functionality and integrate support for a cryptographic system. Work consisted of developing the encryption mechanism, assessing its resilience to error propagation, and developing the protocol to work over a simulated network. The result of the study is a proof of concept that the protocol designed is feasible, applicable, and could be used as a communication standard in future projects. | | | | | | |
| **14. SUBJECT TERMS**   lowercase all terms, except proper nouns | | | | | | **15. NUMBER OF PAGES** |
| **16. PRICE CODE** |
| **17. SECURITY CLASSIFICATION OF REPORT**  Unclassified | **18. SECURITY CLASSIFICATION OF THIS PAGE**  Unclassified | | **19. SECURITY CLASSIFICATION OF ABSTRACT**  Unclassified | | | **20. LIMITATION OF ABSTRACT**  UU |

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)

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**DEVELOPMENT OF INFORMATION ASSURANCE PROTOCOL FOR LOW BANDWIDTH NANOSATELLITE COMMUNICATIONS**

Cervando A. Banuelos II

Rank, Branch of Service (spell out completely)

B.S., Texas A&M University, 2013

Submitted in partial fulfillment of the

requirements for the degree of

**MASTER OF SCIENCE IN COMPUTER SCIENCE**

from the

**NAVAL POSTGRADUATE SCHOOL**

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ABSTRACT

Nanosatellites provide a light, efficient, and cost effective way for research institutions to carry out experiments in low Earth orbit. These satellites frequently use the ultra-high and very high frequency bands to transfer their data to the ground stations, and oftentimes will use the internet protocol and the Transmission Control Protocol as a standard for communication to ensure the arrival and integrity of the data transmitted. Due to bandwidth limitations and signal noise, these connection-based protocols end up accruing a large data bandwidth cost in headers and retransmission costs. Furthermore, due to connection unreliability, encryption and integrity checks present a challenge.

The aim of this thesis was to develop a software based low-bandwidth reliable network protocol that can support a cryptographic system for encrypted communications using commercial off-the-shelf components. This protocol would reduce the data overhead, retain the retransmission functionality and integrate support for a cryptographic system. Work consisted of developing the encryption mechanism, assessing its resilience to error propagation, and developing the protocol to work over a simulated network. The result of the study is a proof of concept that the protocol designed is feasible, applicable, and could be used as a communication standard in future projects.

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LIST OF ACRONYMS AND ABBREVIATIONS

COTS commercial off-the-shelf

IP Internet Protocol

TCP Transmission Control Protocol

UHF ultra-high frequency

VHF very-high frequency

UDP User Datagram Protocol

NERDP Nanosatellite Encrypted Reliable Datagram Protocol

LEO low Earth orbit

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EXECUTIVE SUMMARY

Required or recommended for the departments listed in our Abstracts versus Executive Summaries guidance [here](http://my.nps.edu/web/thesisprocessing/resources), under the “Style and Grammar” section. Please consult your advisors for their preferences regarding length and style.

The executive summary should be able to stand apart from the thesis. Therefore, if you include figures or tables in your executive summary, do not apply the figure or table styles to the titles. Instead, use **NORMAL** style and manually format the title to match the titles in the body of the thesis. This will keep these titles out of the lists of figures and tables, and allow the figure and table numbering to start at “1” in the thesis body, as required.

If you include *parenthetical* citations (APA style, for example) in the executive summary (but weaving your sources directly into your sentences is preferable), include a separate reference list at the bottom of the last page of the summary. Use the same citation/reference format as in the body of the thesis.

**References**

You may include a separate reference list for the executive summary or weave your sources into the narrative.

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ACKNOWLEDGMENTS

Optional for all departments. Acknowledgments may be more informal in tone than the main thesis text but should still follow correct use of sentence structure, grammar, and punctuation.

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# INTRODUCTION

## rESEARCH DOMAIN

Nanosatellites are small low Earth orbit (LEO) devices used to undertake space-based research in a cost effective manner. Nanosatellites typically have a mass of 1-10 kilograms, have a short life time of a few weeks or months in orbit, and are often constructed using commercial off-the-shelf (COTS) components. COTS components are typically inexpensive, readily available, and can be easily repurposed for space missions. The use of these components helps keep the mission prices low and allows for a larger number of research institutions to carry out experiments and demonstrations in LEO.

Currently, nanosatellites and their COTS components rely heavily on pre-existing and well established communication protocols. These protocols are the same ones used in ground based internet communications and build on the Internet Protocol (IP) stack. Specifically, researchers will use two of the most common protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). These protocols operate at a network level on all computers on the ground, and provide a framework for communication to automate the transmission and receipt of data.

TCP is a connection-based protocol, meaning that it relies heavily on a persistent connection even if the connection is noisy or prone to errors in the data. TCP provides key services that are fundamental to the transmission of data such as retransmission of lost or deformed packets, acknowledgement of data received, integrity checks, and the ability to assemble the packets of data in the correct order. To achieve this, each TCP packet will contain anywhere between 20 to 60 bytes of data as a header containing the relevant information needed by the receiver to carry out these functions.

UDP on the other hand is a lighter protocol that does not rely on a persistent connection. UDP is a unidirectional packet sent by a transmitter to a receiver without any information for retransmission, or correct packet ordering. If an object is fragmented into discrete packets and transmitted with UDP, unlike TCP, these packets may or may not arrive, and they may or may not arrive in the right order without any mechanism to verify their order, without a mechanism to acknowledge their successful arrival to the recipient, and no way for the recipient to request the retransmission of a specific packet. UDP does provide a checksum for integrity validation of the packet, but not much more data is transmitted in its 8-byte header.

These data packets are frequently transmitted by nanosatellites over ultra-high and very-high frequency (UHF and VHF) bands. These radio frequencies allow researchers and the operators of the nanosatellites to communicate with the devices in orbit at a low financial cost as transmitting and receiving equipment is COTS. By using these bands, nanosatellite operators can also reduce the power consumption and internal space footprint of the communications components within the nanosatellite.

Nanosatellites provide an accessible opportunity for more institutions to carry out space-based research. The devices have lower expenses than other space missions, small, and the components are readily available to anyone. Since the launch of the first nanosatellites in the early 2000’s, the benefits provided rely heavily on the low cost and profile of the devices. Furthermore, the ability to transmit and receive the data from the devices is beneficial to research institutions who would otherwise have no way to extend their research projects to space exploration. To this end, it is important that a standard in data communication and transmission for nanosatellites be established to broaden the scope of the research capabilities of the nanosatellites. Said standard should take into account the technical limitations of the nanosatellites, be flexible in its application due to the various nanosatellite designs, be a software based solution, and provide an efficient mechanism for communication that improves upon existing communications protocols.

## Research problem and Motivation

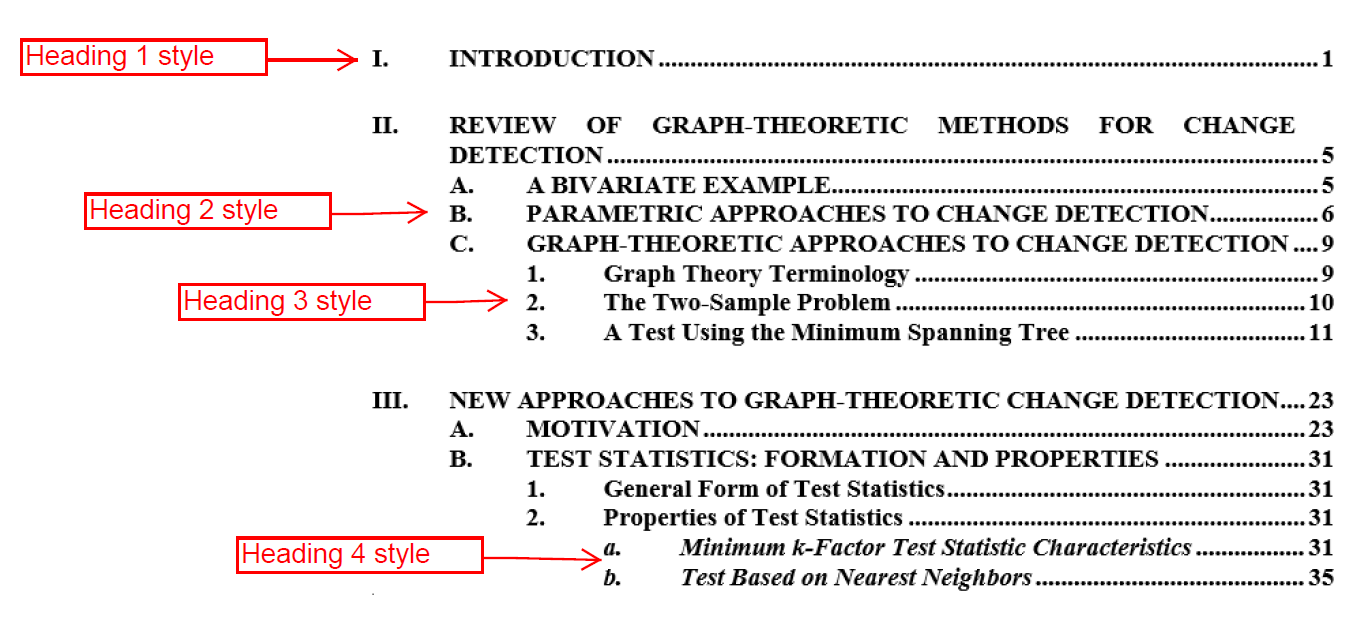
The popularity of nanosatellites is due to largely to their relative simplicity and affordability. Unfortunately, these benefits come at a cost. These costs translate to signal noise, low-bandwidth, high packet drop rates, and low overall mission data transfers. These costs exacerbate the situation by limiting the range and length of experiments accessible and available, and by limiting the usage of well-established IP communication schemes and encryption methods

To make nanosatellites more accessible to multiple research institutions, researchers have designed nanosatellites to communicate over amateur radio bands in UHF and VHF using a variety of radio protocols. As mentioned above, the use of these protocols and these bands means that there is a relatively low data transmission rate accessible for space to ground communications. Surveys done by two teams, Bryan Klofas et al. in 2008, and Paul Muri and Janis McNair in 2012, show that nanosatellites, specifically CubeSats operating in the UHF band, are typically have a baud rate ranging from 1200-9600 [1], [2]

To each heading topic, apply the heading style (**Heading 1**, **2**, **3**, **4**,or **5**) that corresponds to its level in your outline (see Figure 1). When you apply each heading style, the proper letter or number will automatically appear, and formatting will be applied. Figure 1 shows how the heading styles display your thesis outline in the Table of Contents, once they are applied to thesis text. Use headings only to introduce a new section of thesis text. Place paragraph text under each heading before introducing the next level of heading. There must be at least two headings for each heading level (A and B, 1 and 2, *a* and *b*, at minimum), or do not use the heading.

Note that **Heading 3s** and **Heading 4s** must be typed in uppercase and lowercase letters. Do not use **Heading 3s** to make a numbered list; use the **List Number** style or **List Bullet** style to accomplish that task.

**Heading 5** typically is used for subsections below the **Heading 4** level (see Chapter II, pp. 12–13). **Heading 5** also may be used under any heading level to number a series of single paragraphs (see Chapter II, p. 15–16).



When heading styles 1 through 3 are applied to text, they will appear in the Table of Contents.

1. Heading Levels and Their Associated Styles. Adapted from  
   Hawks (2015).

## BODY TEXT STYLES

To all paragraphs in the document, apply **ALL PARAGRAPH** style. There are styles for other elements (e.g., **FIGURE TITLE**, **List Bullet**, **List Number, Quote**) used within the body text.

### Figures

Formatting for figures in NPS theses may be different from what you are used to; therefore, please read and follow these instructions carefully. Figures 1 through 4 of this template show examples of the preferred format in various combinations of the possible elements. Figures 5 and 6 show accepted format variations.

* Figures should be styled as **IMAGE**. This centers the image and applies even white space.
* Do *not* include a title within your image, since it will be written in the figure’s caption, **hereafter called a “Figure Title.”** If a *borrowed* figure contains a title inside it, your Figure Title must be different.
* All figures should be readable if the words in them are meant to be read. You may need to re-create images when the source text is too fuzzy to read. Or, you may need to enlarge the image and place it on a horizontal page. Do this by inserting a “Continuous Section Break” at the start *and* end of your horizontally aligned information and changing the page orientation to “landscape.” Section breaks are available in Word’s “Page Layout” tab.
* In the body text, each figure must be referred to by its number prior to displaying the figure. Refer, for example, to Figure 23, without including its title.
* Although your figures must be explained in your text before they appear, their meaning must also be clear enough to stand alone.
* In your text, *do not* use descriptive words such as “above” or “below” when referring to figures.



**IMAGE** style—centers the image, puts correct spacing above and below

**FIGURE TITLE** style. If you choose to use sentence case (not shown), do so for *all* Figure Titles.

1. A Basic Figure

#### Figure Titles

Each figure must have a title. Type the title *outside* of the actual figure. Follow these NPS thesis style guidelines for Figure Titles, which, in some disciplines, are referred to as captions:

* Type your Figure Title *below* the figure itself, as shown in Figure 2.
* Use a short, definitive title that tells your reader the main topic and the main takeaway from your image.
* Try to limit your title to fewer than 12 words, since these will appear in your List of Figures.
* Use sentence fragments, *not* complete sentences.
* Use either title case or sentence case—*just be consistent with all your Figure Titles*. If you use title case, capitalize all words *except* prepositions, articles, and conjunctions. If you use sentence case, capitalize the first word, any proper nouns, and any word after a colon.
* Do not end a Figure Title with a period, *unless* the title is followed by a citation; adding citations to Figure Titles is covered next in Section b.

Once you have your title typed in, apply **FIGURE TITLE** style to the title. Word automatically inserts the word “Figure,” a sequential number, and a tab space for you, as shown previously in Figure 2.

#### Figure Citations

A citation is *required* if you did not wholly create the image or information yourself; placement of the citation is shown in Figure 3. A citation is not needed when all elements of the figure are your own creation.

For any figure that is not your original work, you must cite the source as part of the **FIGURE TITLE**, using the short-form citation for your chosen citation style.

* Place a period and space after the Figure Title but before the citation.
* If the figure is directly reproduced from a reference, use “Source: \_\_\_.”
* If you changed the original figure, use “Adapted from \_\_\_.”
* Chicago Notes and Bibliography users may use a footnote after the Figure Title instead of “Source:” of “Adapted from”: Figure 3. Caption Here12
* When the source is a webpage, include the name of the website owner; the URL alone is not sufficient.



Place citation, if applicable, after the title, as a new sentence.

Start citation with either “Source:” (exact image borrowed) **or** “Adapted from” (original was altered).

Citations should follow the same format as the reference style you use in your thesis text.

1. A Figure with a Title and a Citation in APA Style. Source:  
   Doe (2017).

NOTE: If you need to provide a full citation, or your sources are numerous, place it in a Secondary Caption (covered next in Section c), not with the Figure Title.

NPS theses and dissertations must comply with U.S. copyright law when using figures, illustrations, and images created by others. Those found in U.S. federal government documents are rarely copyrighted, but this should not be assumed.

You have several options when incorporating another person’s copyrighted work into your document: 1) obtain permission from the copyright owner, 2) follow item-specific licensing rights and restrictions, or 3) determine fair use, an exemption provided in U.S. copyright law for education and research. A determination of fair use must be made on an image-by-image basis, using a [four-factor fair use test](https://www.lib.umn.edu/copyright/fairthoughts).  For more fair use guidance, visit the [Dudley Knox Library’s Fair Use page](http://libguides.nps.edu/copyright/fairuse). For more information on copyright at NPS, visit the [Dudley Knox Library’s Copyright page](http://libguides.nps.edu/copyright/home).

#### Figure Secondary Captions, Separate from Figure Title (Optional)

Depending upon your discipline’s norms, you may need more than a summary Figure Title, whether to include justification for using the source, explain why certain data were presented and other data omitted, or provide more information about methodology used, for example. This additional information must be placed in a “secondary caption.” Refer to Figure 4 for an example of the format.



Secondary Caption. Optional extra information goes directly below the figure. Apply **Figure Secondary Caption** style.

If you would like to provide more information than what is in the Figure Title, provide it here, in a Secondary Caption. Apply **Figure Secondary Caption** style to Secondary Captions.

1. Placement of Optional Secondary Captions in Figure Title

You may add a Secondary Caption *between* the figure and the Figure Title:

* Write Secondary Captions in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case (capitalize first word and proper nouns only).
* Apply **Figure Secondary Caption** style to this secondary text by highlighting it and selecting the style from your Styles palette.

#### Optional Figure Format: Multi-Line Figure Titles, Combining Figure Title and Secondary Caption

Depending upon your discipline’s norms, Figure Titles may be composed of more than one sentence, to include justification for using the source, explanation on why certain data was presented and other data omitted, or more information about methodology used. See Figure 5 for an example of a multi-line Figure Title.

Create multi-line Figure Titles as follows:

* Use a sentence fragment, not a complete sentence, for the first sentence, which summarizes the primary point of the image.
* If you are adding source information, place a period and space after the first sentence and then type the citation in its own sentence.
* Write all other (secondary) sentences in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case for all other sentences after the first and the citation.
* Insert a “style separator” *before* secondary caption text. [Get the instructions here](https://my.nps.edu/documents/105790666/106471207/Multiline_Figure_Title_Instructions.pdf). These secondary captions will remain in your text as a continuation of the Figure Title but will *not* appear in your List of Figures.

**Optional format:** Multi-line Figure Titles are also accepted, provided only the first line is visible in the List of Figures

*See Section d for format instructions*



1. Variation—Multi-Line Figure Title, with First Sentence Only in List of Figures. Adapted from Doe (2017).

You will need to insert a style separator after the Figure Title and before secondary text; instructions are provided in Section d. Use sentence case in secondary text.

#### Optional Figure Format: Figure Title above Figure

You may elect to place all of your Figure Titles ***above*** your figures. In this case, place the more detailed Secondary Caption *below* the figure:

* Write Secondary Captions in *complete* sentences, not fragments, unless you are listing legend elements.
* Use sentence case.
* Apply the **Figure Secondary Caption** style to this secondary text by clicking into it and selecting the style from your Styles list.
* Your thesis processor will adjust your **IMAGE**, **Figure Title, and Figure Secondary Caption** styles to accommodate this optional format. Please do not attempt to do this yourself.
* Refer to Figure 6 for an example of this format.

1. Variation—Figure Title above Figure



***Optional format***:   
If you choose to place Figure Titles ***above*** your figure, do so for ***all*** figures

If you placed all of your Figure Titles above your figures, then place the Secondary Caption **below** the figure, as shown here. Your thesis processor will adjust your **IMAGE**, **Figure Title**, and **Figure Secondary Caption** styles during your Initial Review to accommodate this format.

### Tables

Follow the NPS thesis style guidelines for Figure Titles, with these exceptions:

* Table Titles are to be placed *above* the tables themselves, never below.
* Apply **TABLE TITLE** style to each short, descriptive Table Title. The template will insert “Table” followed by the sequential number, a period, and a tab space before your descriptive title.
* Notes or legends should be placed *underneath* the table and must be aligned with the left side of the table and placed *underneath* the table. Apply **TABLE NOTES** style to these additional descriptive details. After applying the **TABLE NOTES** style, on the “View” tab, check the “Ruler” box to see the ruler. Click on the square underneath the triangles to the left and drag the notes in place.
* Use **Normal** style on the tables themselves, do not use IMAGE style.
* Place citation, if any, after the Table Title, as its own sentence. See   
  Table 1 for an example of where to place the citation.
* If the table is directly reproduced from a reference, use “Source: \_\_\_.”
* If you have made changes to the original table, use “Adapted from \_\_\_.”
* If you need to use the full citation, or if your sources are numerous, place the citation in Table Notes.

**Tables must be no wider than paragraphs.** Landscape the page if needed.

1. Styles to Use and Element Placement for Figures and Tables.  
   Source: [5].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Style to Use on Picture** | **Style to Use on Title** | **Placement of Title** | **Style to Use**  **for Extra Information** | **Placement**  **of Extra Information** |
| **FIGURE**  **Preferred Format**a | IMAGE | FIGURE TITLE | Below figure | Figure Secondary Caption | Between figure and Figure Title |
| **FIGURE**  **Optional Format** | IMAGE | FIGURE TITLE | Below figure | None—Figure Title  is composed of multiple sentencesb | N/A |
| **FIGURE**  **Optional Format** | IMAGE | FIGURE TITLE | Above figure | Figure Secondary Caption | Below figure |
| **TABLE** | Normal | TABLE TITLE | Above table | TABLE NOTE | Below table |

You many include notes or a legend underneath a table. Align them with the left side of the table.

aPick one of the figure formats offered in this table and use it consistently throughout your thesis.

bSee Section d for instructions on how to do multi-line Figure Titles.

Add another paragraph return under each table to separate the table from the text

Apply **TABLE NOTE** style to notes

Align Table Notes with left side of table. (In the View tab, select Ruler to show ruler. Click on the square under the left triangles and drag in place).

### Bulleted and Numbered Lists

Guidance for bulleted or numbered lists is as follows:

* Apply **List Bullet** style to bulleted lists and **List Number** style to numbered lists.
* To restart a numbered list at “1,” right click on the first item and choose “Restart at 1.”
* Avoid using a mixture of bullets, numbers, or dashes, for different lists in your thesis.
* Generally, bulleted and numbered lists are punctuated with periods only if the bullets consist of complete sentences.

### Block Quotes

Quotations of five or more lines are to be styled as **Quote** style, with no quotation marks around the quote. This signals that the material is quoted. For formatting purposes only, the quotation becomes a separate paragraph. Citations go outside the period (block quotes only).

Remove quotation marks from around block quotes

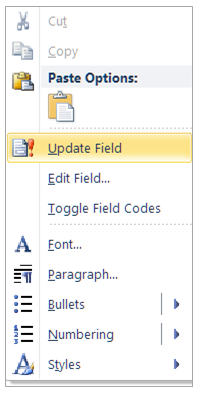
Quotations are understood to be excerpts; therefore, ellipses are usually not used at the beginning of a quotation. Ellipses *are* used in the middle of a quotation where a portion of the text has been omitted. This is an example … of correct use of ellipses. Ellipses may also be used at the end of a quote that is grammatically incomplete. For quoted material within a block quote, use double quotation marks. Citations go outside the period for block quotes only, like this. (Naval Postgraduate School, 2017)

To continue the paragraph visually (if desired), remove the paragraph indent from text following a block quotation as shown here (on the View tab, select Ruler. Click on top triangle ruler guide and slide 0.5 inch to left margin).

## Table of contents

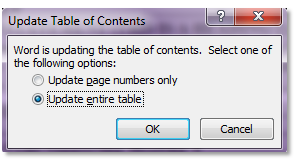
*Do not manually type your own Table of Contents.* After styling all headings in your thesis, right-click on the Table of Contents (text field turns gray).

##### Select Update Field



Crop excessive white space   
from images

##### Then Select Update Entire Table



##### Each heading will appear in proper outline form.

A glance at the completed Table of Contents should provide an overview of the thesis and act like an outline but not weigh down the reader with detailed information. Word will also update the Lists of Figures and List of Tables on command, as described for the Table of Contents.

## zotero, refworks and the like

If you use reference-list generating software, such as RefWorks, ensure that you fill in all fields completely and accurately when creating your citation list. *You must edit the reference list for punctuation and formatting* once the footnotes (if you use Chicago footnote style) and List of References are imported. To edit most lists, you must remove the field code. Do this by pressing Shift + Control + F9 at the same time. In Word’s citation manager, click on the list and choose “convert to static text.” If problems arise, see a Thesis Processor for help.

**RefWorks/Write-N-Cite users:** Before submitting for Final Review, click option to “Remove Field Codes,” after importing the List of References (you will find this option under the “Tools” menu in Write-N-Cite). *Save a copy of the thesis for your records before removing the field codes.* See a Thesis Processor or the library for help.[[1]](#footnote-1)

Also, RefWorks users must abandon the check-in/check-out feature of SharePoint. Instead, download the thesis from SharePoint, make edits, and then reupload the file to SharePoint (Write-N-Cite cannot access files in password-protected sites such as SharePoint).

The library offers citation management tools [here](http://libguides.nps.edu/citation/management).

## blank pages

Place each new chapter on an odd-numbered page (this should be done before submitting for Final Review). You may need to remove or insert intentional blank pages to achieve this. To add a blank page, place the cursor after the last word on the current page, then press Control + Enterto insert a new page in your file. On the style list, click **BLANK PAGE**. Type “THIS PAGE INTENTIONALLY LEFT BLANK.”

## Cross referencing

Referring to the wrong figure/table number is a top error found in final reviews!

You must mention each figure and table by label and number in your narrative. If you have many figures and tables, you might want Word to keep track of the figure and table numbers for you as you write and revise. Follow these steps to have Word insert cross references for you:

1. First, remove the period and tab from the **FIGURE TITLE** and **TABLE TITLE** styles (Style Palette🡪right click on style name🡪modify🡪format🡪numbering🡪define new number format).
2. To insert a cross reference, in the **References** tab, click **Cross-reference**. Choose **Numbered item** under “reference type,” and **Paragraph number** under “insert reference to.”
3. To update the cross references as you work, select all text (Control + A) and press F9. Follow prompts to update all linked content.
4. Next, when you are sure all figures and tables are in their permanent positions, highlight all **body** text starting from page 1 and press Shift + Control + F9. This breaks the field code from the cross references.
5. Finally, reinsert the period and tab in the **FIGURE TITLE** and **TABLE TITLE** styles.

## equations

To create equations, use MathType, which you can download from the NPS Technology [webpage](http://www.nps.edu/Technology/Downloads/SoftwareLibrary.html). DO NOT use the Insert, Equation option in Microsoft Word because math symbols could disappear when the file is converted to PDF. Do not clear coding from your thesis in one fell swoop by selecting all text and removing the code. Doing this will end up converting all of your equations to pictures.

The most popular format for equations is to center them and place the equation number on right margin (choose “Right-numbered” equation in MathType to achieve this). Whether you number your equations is at your discretion.

5x=10 (1)

If you created equations outside of MathType, or if you created equations in MathType without first numbering them but now want them numbered, follow these instructions:

1. Place your cursor in front of the equation, go to your style list, and choose either **Equation** or **MTDisplayEquation**.
2. Then, press tab. Your equation should jump to center of the page. If it does not, remove extraneous space and tab markings. There should be only one tab space.
3. Place your cursor *after* the equation and press tab. The cursor will jump to the right margin.
4. Now click **Insert Number** on the MathType menu if you want MathType to number your equations (to format the numbers, click **Insert Number**). Or, you can manually number your equations.

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# SAMPLE CHAPTER

Do no parrot headings (notice this is an immediate repeat of the chapter title) if you immediately begin a chapter with a subsection heading

**~~X. SAMPLE CHAPTER~~**

This is how a properly formatted chapter would look. Each section of a chapter should be substantial enough to warrant a heading. *There should be at least two sections per subheading level*. *Do not stack headings without text in between*. Heading 5 style may be used under any heading level if short, numbered paragraphs are desired.

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# appendix. Optional

Appendix titles are also styled as **Heading 1**, minus a roman numeral—backspace to remove the roman numeral. Then, type “Appendix,” two spaces, a letter, and a title: “APPENDIX A. DATA.” *However,* *if you have only one appendix, do not add the letter “A.”*

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# List of References

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| --- | --- |
| [1] | B. Klofas, J. Anderson and K. Leveque, "A survey of CubeSat communication systems"," in *5th Annual CubeSat Developers' Workshop*, 2008. |
| [2] | P. Muri and J. McNair, "A survey of communication sub-systems for intersatellite linked systems and CubeSat missions," *Journal of Communications,* vol. 7, no. 4, pp. 290-308, 2012. |

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