INGESTION OF IONOSPHERIC SCINTILLATION SKYMAPS INTO GNSS ALGORITHMS

Matthieu Lonchay was born in 1986 and grew up in Ozo (Durbuy), a small village at the edge of the Ardenne in Belgium, on the land of his farm family.

Passionate about Earth Sciences and Space Technologies, he obtained a Master of Science in Geomatics and Surveying from the University of Liège (ULiège), Belgium, in 2009. His Master thesis dedicated to Global Navigation Satellite Systems (GNSSs) was awarded the ODISSEA Prize by the Senate of Belgium.

Motivated by the launch of Galileo, the European GNSS, Matthieu started his career and pursued his education with the completion of this PhD thesis dedicated to GNSSs. He conducted this project as an FNRS Research Fellow (Belgian National Fund for Scientific Research) within the Geomatics Units of the University of Liège in collaboration with the Nottingham Geospatial Institute (NGI) of the University of Nottingham (UoN), United Kingdom. In the framework of his research, Matthieu exploited his background in Geomatics and designed a methodology to produce real-time ionospheric scintillation skymaps for prototyping mitigation strategies aiming to enhance the performances of GNSS algorithms in case of low-latitude ionospheric scintillations. He was awarded the DEHAY Prize by the University of Liège for his PhD thesis which also fulfilled the criteria to receive the European PhD Label.

In 2017, Matthieu joined Septentrio, a high-end GNSS receiver manufacturer located in Leuven, Belgium, where he pursues his career as a GNSS Algorithm Engineer.

Beside his passion for Earth Sciences and Space Technologies, Matthieu is also an avid rock climber and a qualified climbing instructor from the Belgian Alpine Club (CAB). During his free time, he also enjoys trail running and cycling up and down the steep trails and roads of his native Ardenne.

INGESTION OF IONOSPHERIC SCINTILLATION SKYMAPS
INTO GNSS ALGORITHMS

MATTHIEU LONCHAY

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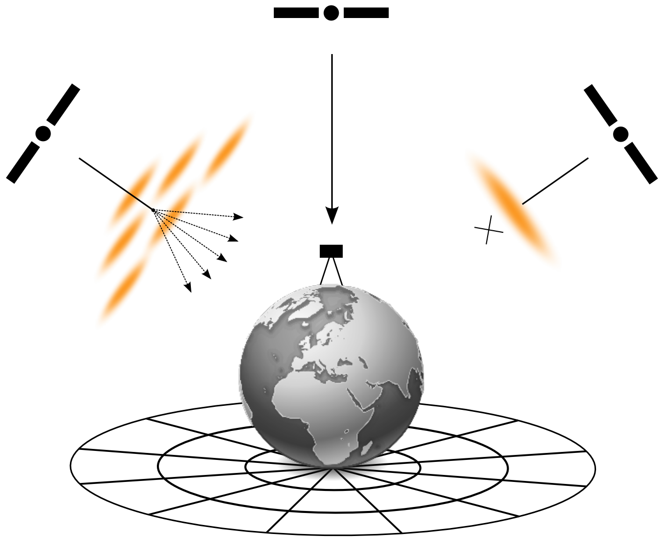

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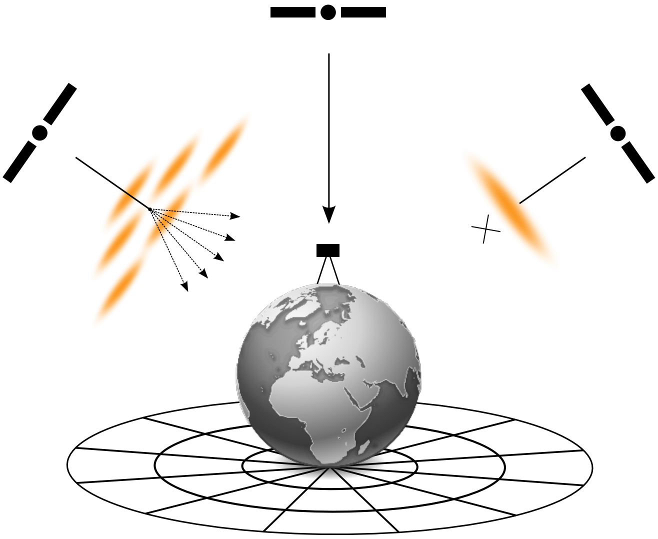

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Jury

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The research described in this PhD thesis was conducted within the Geomatics Unit of the University of Liège, Belgium, in collaboration with the Nottingham Geospatial Institute (NGI) of the University of Nottingham (UoN), UK. This PhD thesis fulfilled the criteria to receive the European PhD Label.

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INGESTION OF IONOSPHERIC SCINTILLATION SKYMAPS INTO GNSS ALGORITHMS

ABSTRACT

Nowadays, Global Navigation Satellite Systems (GNSSs) play a significant role in our modern society as they support a wide range of applications worldwide associated with utterly demanding performance requirements. However, GNSS performances in terms of accuracy, continuity and reliability are limited by the Earth's ionosphere. In particular, small-scale irregularities and inhomogeneities in the ionospheric free-electron density are responsible for diffraction and scattering effects on GNSS signals that propagate through such ionospheric disturbances. These effects result in rapid fluctuations of the amplitude and phase of GNSS signals, also known as *ionospheric scintillations*, which can severely disrupt the performances of GNSS navigation and positioning algorithms.

The ultimate objective of this PhD thesis consists in prototyping mitigation strategies in order to improve the accuracy, continuity and reliability performances of GNSS algorithms in case of low-latitude ionospheric scintillations. In particular, this research targets two specific Single-Point Single-Epoch (SPSE) GNSS algorithms, namely the Standard Point Positioning (SPP) and the Precise Point Positioning (PPP) algorithms. The mitigation strategies prototyped in the framework of this research are based on ionospheric scintillation skymaps resulting from the application of specific spatial analysis techniques on ionospheric scintillation measurements. Specifically, these prototype mitigation strategies target the stochastic modelling and the integrity monitoring stages of the SPP and PPP algorithms.

First, this PhD thesis presents a statistical analysis based on measurements performed by a network of Ionospheric Scintillation Monitoring Receivers (ISMRs) located near the magnetic equator in Brazil and collected during the year 2014, i.e. during the (second) peak of the last solar maximum (solar cycle 24). This statistical analysis leads to the conclusion that high-end GNSS receivers operating in low-latitude regions can see their positioning performances affected by ionospheric scintillations during about 20%–30% of the time in case of active ionospheric conditions. The addition of detrimental effects due to signal fading, cycle slips and losses of signal lock results in poor positioning performances in terms of accuracy, continuity and reliability during moderate-to-intense ionospheric scintillation events. As the performances of the PPP algorithm rely on the precision of carrier phase measurements, the PPP algorithm is more sensitive to ionospheric scintillations than the SPP algorithm, which is based on code pseudorange measurements exclusively. In case of active ionospheric scintillation conditions, the Root-Mean-Square Error (RMSE) of the tridimensional PPP solution can be as high as 6.73 m and its success rate as low as 50% by comparison to 0.18 m and about 100%, respectively, during quiescent conditions.

Then, this PhD thesis focusses on the spatiotemporal characteristics of ionospheric scintillations by exploiting spatial analysis techniques applied to scintillation measurements collected through the experimental ISMR network located in Brazil. Spatial analysis techniques consider densified ionospheric scintillation skyplots composed of Ionospheric Pierce Points (IPPs) as spatial samples whose geometric and attribute components evolve over time as satellites are orbiting the Earth and as ionospheric conditions change. This approach turns out to be successful in detecting, scaling and tracking significantly positive spatial autocorrelation in ionospheric scintillation skyplots during active ionospheric conditions. The spatial analysis techniques exploited in the framework of this research eventually led to the design of three types of real-time ionospheric scintillation skymaps that quantify the spatiotemporal characteristics of low-latitude ionospheric scintillations.

Finally, this PhD thesis describes the design and benchmarks the performances of several categories of prototype mitigation strategies against ionospheric scintillations that target the stochastic modelling and the integrity monitoring stages of the SPP and PPP algorithms. The design of the strategies is based on several types of ionospheric scintillation skymaps and the benchmark of their performances relies on the definition of several specific performance parameters. Globally, all the prototype mitigation strategies designed in the framework of this PhD thesis contribute to increase the accuracy, continuity and reliability performances of the SPP and PPP algorithms during low-to-moderate ionospheric scintillations. Strategies associated with ionospheric scintillation skymaps based on local spatial autocorrelation statistics outperform strategies based on interpolated skymaps. Strategies related to the weighting scheme of the stochastic model provide better results for the SPP algorithm than the PPP algorithm whose performances are further enhanced by strategies implementing spatial masks. Prototype mitigation strategies tuning the integrity monitoring stage of the SPP and PPP algorithms increase significantly the continuity and reliability performances of the algorithms but at the expense of a heavier computational load. Best performances for the SPP and PPP algorithms in terms of reliability are obtained by hybrid strategies targeting both the stochastic modelling and the integrity monitoring stages of the algorithms.

RÉSUMÉ

Les systèmes globaux de positionnement et de navigation par satellites (*Global Navigation Satellite Systems – GNSSs*) occupent désormais une place prépondérante dans notre société moderne. En effet, ils supportent une multitude d'applications de par le monde qui nécessitent des performances sans cesse croissantes en termes d'exactitude, de continuité et de fiabilité. Cependant, les performances du positionnement par satellites sont limitées par l'ionosphère terrestre. En particulier, les irrégularités dans la densité en électrons libres de l'ionosphère sont responsables d'effets de diffraction et de dispersion sur les signaux GNSS qui se propagent au travers de telles perturbations ionosphériques. Ces effets se traduisent par des fluctuations rapides de l'amplitude et de la phase des signaux GNSS, aussi désignées sous le vocable *scintillations ionosphériques*, qui peuvent sévèrement dégrader les performances des algorithmes de positionnement et de navigation par satellites.

L'objectif ultime poursuivi par cette Thèse de Doctorat consiste à développer des prototypes de stratégies d'atténuation des effets des scintillations ionosphériques afin d'améliorer les performances des systèmes de positionnement par satellites en cas de scintillations ionosphériques équatoriales. En particulier, cette recherche cible deux algorithmes de positionnement par satellites, à savoir le *Standard Point Positioning (SPP)* et le *Precise Point Positioning (PPP)*. Les stratégies d'atténuation prototypées dans le cadre de cette recherche sont basées sur des cartes de scintillations ionosphériques qui résultent de l'application de techniques d'analyse spatiale sur des mesures de scintillations ionosphériques effectuées à l'aide de récepteurs GNSS spécialement conçus à cet effet (*Ionospheric Scintillation Monitoring Receivers – ISMRs*). Plus spécifiquement, ces stratégies ciblent les étapes de la modélisation stochastique et du contrôle d'intégrité des algorithmes SPP et PPP.

Tout d'abord, cette Thèse de Doctorat présente une analyse statistique basée sur des mesures effectuées par un réseau de récepteurs de type ISMR implanté à proximité de l'équateur magnétique, au Brésil. Les mesures ont été collectées durant l'année 2014, c'est-à-dire durant le (second) pic d'intensité du dernier maximum solaire (cycle solaire n°24). Cette analyse statistique mène à la conclusion que les récepteurs GNSS opérant dans des régions de basse latitude peuvent voir leurs performances de positionnement affectées par des scintillations ionosphériques durant 20%–30% du

temps en cas de conditions de scintillations ionosphériques actives. La combinaison d'effets néfastes engendrés par des atténuations de signal, des pertes de verrouillage de signal et des sauts de cycles entraîne une forte baisse des performances des algorithmes SPP et PPP en termes d'exactitude, de continuité et de fiabilité. Etant donné que les hautes performances de l'algorithme PPP dépendent de la précision de mesures de phase, l'algorithme PPP est davantage sensible aux scintillations ionosphériques que l'algorithme SPP, basé exclusivement sur des mesures de code. En cas de scintillations ionosphériques sévères, la racine carrée de l'erreur quadratique moyenne (*Root-Mean-Square Error – RMSE*) de la solution PPP peut atteindre la valeur extrême de 6.73 m et s'associer à un taux de succès aussi faible que 50%, par comparaison à une valeur de 0.18 m et de 100%, respectivement, pendant des conditions nominales.

Ensuite, cette Thèse de Doctorat se focalise sur les caractéristiques spatio-temporelles des scintillations ionosphériques au moyen de techniques d'analyse spatiale appliquées à des mesures de scintillations ionosphériques collectées au travers du réseau expérimental implanté au Brésil. Ces techniques d'analyse spatiale considèrent des cartes du ciel, dénommées *skyplots*, représentant des échantillons spatiaux densifiés composés de points de percée ionosphériques (*Ionospheric Pierce Points – IPPs*) associés à des mesures de scintillations ionosphériques. Ces échantillons sont caractérisés par des composantes géométrique et attributaire qui évoluent au cours du temps étant donné que les satellites GNSS se déplacent continuellement sur leurs orbites respectives et que l'état de l'ionosphère varie également au cours du temps. Cette approche s'est révélée particulièrement efficace pour détecter, mesurer et localiser la présence d'autocorrélation spatiale significativement positive dans des skyplots de scintillations ionosphériques en cas de conditions actives. Les techniques d'analyse spatiale exploitées dans le cadre de cette recherche permettent de construire trois types de cartes de scintillations ionosphériques qui ont la capacité de quantifier les caractéristiques spatio-temporelles des scintillations ionosphériques équatoriales en temps réel.

Enfin, cette Thèse de Doctorat décrit la construction de plusieurs catégories de prototypes de stratégies visant à limiter l'impact des scintillations ionosphériques sur les performances des algorithmes SPP et PPP. Ces stratégies visent tout particulièrement les étapes de la modélisation stochastique et du contrôle d'intégrité des algorithmes SPP et PPP. Elles sont établies sur base des cartes de scintillations ionosphériques élaborées précédemment. Les différentes stratégies prototypées sont ensuite mises au banc d'essai afin d'évaluer et de comparer leurs performances en termes de positionnement selon plusieurs critères spécifiques. Globalement, toutes

les stratégies d’atténuation prototypées dans le cadre de cette recherche contribuent à l’amélioration des performances en termes d’exactitude, de continuité et de fiabilité des algorithmes SPP et PPP en cas de scintillations ionosphériques équatoriales modérées. Les stratégies d’atténuation associées à des cartes de scintillations ionosphériques basées sur des indices d’autocorrélation spatiale locale surclassent les stratégies basées sur des cartes de scintillations ionosphériques interpolées. Les stratégies visant la pondération des observations au sein du modèle stochastique fournissent de meilleurs résultats pour l’algorithme SPP que pour l’algorithme PPP, dont les performances sont davantage améliorées par l’utilisation de masques spatiaux. Les prototypes de stratégies d’atténuation qui optimisent l’étape du contrôle d’intégrité des algorithmes SPP et PPP augmentent considérablement les performances des algorithmes en termes de continuité et de fiabilité mais elles impliquent également une hausse significative de la charge de calcul associée. Les meilleurs performances en termes de fiabilité des algorithmes SPP et PPP en cas de fortes scintillations ionosphériques sont obtenues par l’implémentation de stratégies hybrides qui combinent une optimisation du modèle stochastique et du contrôle d’intégrité des algorithmes SPP et PPP.

“Study is not the learning of facts,
but the training of the mind to think.”

Albert Einstein

PREFACE

This book describes the results obtained in the framework of my PhD thesis dedicated to Global Navigation Satellite Systems (GNSSs). As the author, I enthusiastically recommend you to read the seven chapters of this book cover to cover. However, it is worth mentioning that this thesis was designed in such a way that all its chapters stand by themselves, allowing a more selective approach. This aspect is reinforced by the presence of individual summaries, introductions and conclusions for all core chapters (Chapters 2–6) which are completed with a global introduction (Chapter 1) and thorough general conclusions and perspectives (Chapter 7).

As I sit writing these lines, I cannot help wondering how this incredible journey started. As a young high school student, I remember being already attracted by Space Technologies and Earth Sciences. This led me towards a Master of Science in Geomatics and Surveying which was eventually concluded by an entertaining thesis in the field of GNSSs. At the time, the first experimental Galileo satellites, the European GNSS, were already orbiting the Earth and the scientific community was thrilled. I enrolled in a PhD program and joined the Geomatics Unit of the University of Liège (ULiège), Belgium, as a junior researcher. As a welcome gift, I received a pack containing two high-end GNSS receivers manufactured by Septentrio, a successful Belgian company that I would enthusiastically join as a GNSS Algorithm Engineer a few years later. My first mission as a young PhD student was to fully set up a GNSS station to track the first experimental Galileo signals. What a start!

The human brain has the brilliant capacity to first remember positive memories. In addition to this terrific start, I highly enjoyed the process of growing as a researcher and a professional combined with activities such as teaching, managing projects, setting up in-situ experiments, travelling and communicating with people from all over the world. In this regard, I seized the opportunity to establish a collaboration with the Nottingham Geospatial Institute (NGI) of the University of Nottingham (UoN), United Kingdom. This opportunity constitutes one of the highlights of this whole adventure. In addition to a major impact on my research, it was also a great human experience which I gained a lot from. However, the completion of a PhD thesis can also be an emotional roller coaster and mine was no exception to the rule. Dealing with disappointment, doubts and frustration is, so I was told, also part of the PhD experience which, eventually, teaches you to remain humble, to constantly question yourself and, above all, to show strong persistence when faced with hurdles.

To enjoy good times and stay on track during bad times, it is essential to benefit from valuable support around you. In this regard, I want to thank my supervisor, René, for offering me the opportunity to jump into such an exciting field. I am also grateful to all the members of my PhD supervision committee for their valuable feedbacks. If I keep such positive memories about the early stage of my career as a researcher, it is also thanks to the enthusiasm of my first colleague, Benoît. Obviously, I would like to thank all my (former) colleagues at the Geomatics Unit of the University of Liège for their support and contribution to a good research environment. Special thanks to Jean-Paul and Yves for their commitment and trustful support during the last stage of my research. I wish you both all the very best and a happy retirement. Cécile, thank you for having been such a supportive colleague during my endless writing hours. Thank you, Marc, for your constant altruism within the team. See you on a trail soon!

I will always remember the warm welcome I received from Marcio, Craig and Alan at the University of Nottingham. You played a significant role in the successful outcome of my visits to Nottingham. Your judicious suggestions combined with the access to scintillation data gave a highly valuable impulse to my research. I also greatly appreciated the help of Bruno Vani, from the São Paulo State University (UNESP), Brazil, who supported my access to data servers in Brazil. I am very thankful to Prof. Catherine Timmermans from the Department of Mathematics of the University of Liège for her precious suggestions regarding the benchmark of GNSS positioning performances. I also owe deep thanks to Prof. Manuel Hernández-Pajares from the Polytechnic University of Catalonia (UPC), Barcelona, Spain, for his external review allowing me to fulfill the criteria to receive the European PhD Label.

Combining my job at Septentrio and the finalisation of this PhD thesis turned out to be a complex challenge that I would not have been able to tackle without the support of my colleagues at Septentrio, and Frank Boon in particular. Special thanks to my colleague Frank Kleijer for proofreading this document. Hartelijk bedankt!

Finally, I am grateful that I could always rely on my supportive family who acted as a source of strength to reach the end of this project. To my closest friends who I could share many climbing, running and cycling sessions with: you have no idea how much you contributed to this! Merci!

Last but not least, thank you, Lydie, for teaming up with me in life and for supporting me through difficult projects like this one...

CONTENTS

ABBREVIATIONS

A

AERI	Applied Electromagnetic Research Institute
AIA	Atmospheric Imaging Assembly
AIUB	Astronomical Institute of the University of Bern
ASTM	American Society for Testing and Materials
AU	Astronomical Unit

B

BPSK	Binary Phase Shift Keying

C

C/A	Coarse Acquisition
CALIBRA	Countering GNSS high-accuracy applications limitations due to ionospheric disturbances in Brazil
CDMA	Code-Division Multiple Access
CIGALA	Concept for ionospheric scintillation mitigation for professional GNSS in Latin America
CME	Coronal Mass Ejection
CP	Code-minus-Phase
CPU	Central Processing Unit
CS	Commercial Service

D

DST	Disturbance Storm Time
DLL	Delay Lock Loop
DoD	Department of Defense
DOP	Dilution of Precision
DSP	Digital Signal Processor

E

EC	European Commission
EGNOS	European Geostationary Navigation Overlay Service

EIA	Equatorial Ionospheric Anomaly
EKF	Extended Kalman Filter
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESF	Equatorial Spread-F
EU	European Union
EUV	Extreme Ultraviolet

F

FDE	Fault Detection Exclusion
FDMA	Frequency-Division Multiple Access
FIT	Frederik Institute of Technology
FLL	Frequency Lock Loop
FOC	Full Operational Capability
FP7	7th Framework Programme for Research
FST	Faculty of Science and Technology

G

GDOP	Geometric Dilution of Precision
GEO	Geostationary Orbit
GF	Geometry-Free
GIM	Global Ionospheric Propagation Model
GLONASST	GLONASS Time
GNSS	Global Navigation Satellite System
GOS	Getis-Ord standard Score
GPS	Global Positioning System
GPST	GPS Time
GSA	European GNSS Agency
GST	Galileo System Time
GSV	GPS Silicon Valley
GTRF	Galileo Terrestrial Reference Frame
GUI	Graphical User Interface

H

HDOP	Horizontal Dilution of Precision
HZE	High atomic number and high Energy

I

IDW	Inverse Distance Weighting
IF	Ionosphere-Free
IGS	International GNSS Service
IM	Integrity Monitoring
IPP	Ionospheric Pierce Point
IR	Infrared
ISMR	Ionospheric Scintillation Monitoring Receiver
ISS	International Space Station
ITRS	International Terrestrial Reference System
IWLS	Iterative Weighted Least-Squares

J

JPL	NASA Jet Propulsion Laboratory

K

KF	Kalman Filter

L

LASCO	Large Angle and Spectrometric Coronagraph
LT	Local Time
LSA	Least-Squares Adjustment

M

MAVEN	Mars Atmosphere and Volatile Evolution
MW	Melbourne-Wübbena

N

NASA	National Aeronautics and Space Administration
NEU	North-East-Up
NGI	Nottingham Geospatial Institute
NICT	National Institute of Information and Communications Technology
NL	Narrow-Lane
NOAA	National Oceanic and Atmospheric Administration

O

OCXO	Oven-Controlled Crystal Oscillator

OS	Open Service

P

PDOP	Position Dilution of Precision
PLL	Phase Lock Loop
PPP	Precise Point Positioning
PPS	Precise Positioning Service
PRN	Pseudo-Random Noise
PRS	Public Regulated Service
PVT	Position Velocity Time

Q

R

RAIM	Receiver Autonomous Integrity Monitoring
RINEX	Receiver Independent Exchange
RMS	Root Mean Square
RMSE	Root-Mean-Square Error
RSD	Relative Standard Deviation
RTK	Real-Time Kinematic

S

SAC	Spatial Autocorrelation
SAR	Search and Rescue
SBAS	Satellite-Based Augmentation System
SBF	Septentrio Binary Format
SD	Standard Deviation
SDO	Solar Dynamic Observatory
SEP	Solar Energetic Particle
SFU	Solar Flux Unit
SM	Spatial Mask
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine
SNR	Signal-to-Noise Ratio
SOHO	Solar and Heliospheric Observatory
SoL	Safety-of-Life
SPP	Standard Point Positioning
SPS	Standard Positioning Service
SPSE	Single-Point Single-Epoch
SR	Success Rate

SSI	Solar Spectral Irradiance
SSR	State Space Representation
sTEC	Slant Total Electron Content
SSW	Sudden Stratospheric Warming

T

TAI	International Atomic Time
TDOP	Time Dilution of Precision
TEC	Total Electron Content
TECU	Total Electron Content Unit
TSI	Trend Surface Interpolation
TSI	Total Solar Irradiance

U

UK	United Kingdom
ULiège	University of Liège
UNESP	São Paulo State University
US	United States
UoN	University of Nottingham
UPC	Polytechnic University of Catalonia
UTC	Coordinated Universal Time
UV	Ultraviolet

V

VDOP	Vertical Dilution of Precision
vTEC	Vertical Total Electron Content

W

WAAS	Wide Area Augmentation System
WDC	World Data Center
WGS-84	World Geodetic System 1984
WL	Wide-Lane
WS	Weighting Scheme

X

Y

Z

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