Special Study Group 1.182:

"MULTIPATH MITIGATION"

Introduction

The precision of raw carrier phase observations recorded by modern GNSS receivers is generally at the sub-millimetre level. However, in all but the most benign environments, the achievable resolution of GNSS positioning is one or more orders of magnitude worse. This discrepancy between the theoretical hardware-dependent precision of the raw observations and the practical accuracy of GNSS position solutions can, in part, be attributed to the effects of site-dependent electromagnetic scattering of incoming GNSS signals. If millimetre level (or better) GNSS accuracies are to be routinely achieved in the future, these electromagnetic scattering effects (commonly referred to as multipath and diffraction) must be eliminated. The website of the Special Study Group 1.182 is http://www.gmat.unsw.edu.au/snap/gps/iag_section1/ssg1182.htm

Objectives of the SSG 1.182

The goal of the SSG 1.182 is to study GNSS multipath detection and mitigation techniques with the aim of improving existing high precision positioning accuracies. In the context of this SSG, multipath is loosely defined as the systematic errors in raw GNSS observations that are due to any signal scattering effect caused by the local environment surrounding an antenna. Furthermore, this SSG will focus on carrier phase and code-based multipath in terms of effects on receiver operation for high precision applications. Finally, within the scope of the group, the term GNSS is defined to encompass any type of global positioning system (for example, GPS, Glonass-GPS and Galileo-GPS), or systems simulating GNSS signals (such as in the case of pseudolites). The objectives of the group can be summarised as:

Evaluate and compare existing and developing algorithms and techniques for multipath detection and mitigation.

Quantify and document the effectiveness of commercial receiver-based multipath mitigation techniques for high precision positioning.

Investigate and document the properties of multipath in a variety of environments (particularly high risk environments).

Provide information and guidelines for multipath detection and elimination for high precision applications.

Members and Corresponding Members

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Activities of the SSG 1.182

The primary activities of the group since its inception in January 2000 have been:

a. Define the terms of reference and objectives.

b. Compile review of relevant and available literature. A list of some 120 multipath related papers is located at: http://www.cage.curtin.edu.au/~mike/ssg1.182/biblio.htm.

c. Compile review of relevant web sites. A set of links to relevant web sites can be found at: http://www.cage.curtin.edu.au/~mike/ssg1.182/links.htm.

d. Compilation of data archive for multipath data. The SSG is in the process of compiling a data archive to provide multipath researchers with easy access to a variety of different data types from different environments. The archive will also provide reference to the multipath analysis performed by the group who supplied the data, enabling direct comparison between different techniques and different research groups. The archive should be on-line by late 2001.

e. Define core research areas within the SSG's terms of reference. As the terms of reference are rather broad, a number of core research sub-sections have been defined. Individual group members have been encouraged to monitor developments in the sub-sections relevant to their personal fields of expertise. These include:

- multipath characterisation and attitude determination;
- multipath mitigation developments in receiver hardware;
- semiparametric and parametric multipath modelling techniques;
- weighting and SIGMA models for multipath mitigation;
- multipath in space-based applications;
- multipath mitigation using multi-antenna arrays, time stacking and crossing points; and
- electromagnetic propagation modelling for multipath analysis.

Below is a brief summary of the technical developments being covered by this SSG. Full reports from group members can be found at the SSG 1.182 own website: http://www.cage.curtin.edu.au/~mike/ssg1.182/.

Multipath Mitigation Developments in Receiver Hardware

A variety of so-called multipath-mitigating receiver architectures have been developed over the past decade.

Narrow-correlator (NovAtel); Edge correlator (Ashtech) - The narrow-correlator concept involves moving the traditional 'early' and 'late' correlators closer together. The peak of the pseudo-range multipath error envelope is reduced in direct proportion to the correlator spacing. Ultimately the finite bandwidth of the GPS signal places a practical lower bound on the correlator spacing. Correlator spacings of 0.1 and 0.05 chips are commercially available, thus providing approximately a factor of 10 to 20 reduction in the peak of the error envelope.

Multipath-Estimating Delay-Lock Loop (MEDLL) (NovAtel)- The MEDLL uses multiple correlators (6 – 10) per channel in order to determine the shape of the multipath-corrupted correlation function. The MEDLL software determines the best combination of direct and multipath signals (that is, amplitudes, delays, and phases) which could have produced the measured correlation function.

Strobe correlator (Ashtech) - The strobe correlator was developed by Ashtech in 1996 and involves a linear combination of two narrow correlator discriminator functions. The result is a discriminator function which is very narrow and thus is significantly less susceptible to medium and long delay multipath.

Enhanced strobe correlator (Ashtech); Pulse-Aperture Correlator (NovAtel) - For most practical purposes the Enhanced Strobe Correlator exhibits true P-code-like multipath characteristics. Specifically, it is virtually insensitive to multipath with delays longer than 50 metres. More recently, NovAtel has released the Pulse Aperture Correlator which has very similar performance. Other manufacturers (Leica, Navcomm) have similar architecture.

Multipath mitigation through modified antenna design is also an important field of research. The most recent developments include adaptive array techniques in which two classes of solutions have been proposed. A first is based on the joint utilisation of a direction-of-arrival (DOA) estimation technique together with a constrained adaptive algorithm. A second approach uses a self-adaptive constant modules technique, eliminating the need of a pilot signal and DOA estimator.

Multipath Mitigation Using Functional and Stochastic Modelling

One of the most important developments to date in this field are the SIGMA models which were developed to overcome artificially introduced periods of weak satellite geometry by proper weighting of phase observations (SIGMA-ε model) and to reduce signal diffraction effects of the phase observations (SIGMA-Δ model). The main parameter of these models is the ratio of the power of the GPS carrier wave C [dBW] to the noise power density N0 [dBW-Hz], in short C/N0 [dB-Hz]. Usually, geodetic receivers provide the C/N0 measurement in the receiver internal binary format or in the NMEA $GPGSV message. There are currently discussions in progress to standardise and include the C/N0 observation in a future RINEX format of the GPS observation files. Recently, researchers from Leica Geosystems have proposed a self-calibrating SIGMA-Δ weight model.

A different approach to the SIGMA models also uses signal quality indicators such as signal-to-noise ratio (SNR) to reduce the errors due to multipath. Work is concentrating on direct estimation of the size and sign of multipath errors and subsequent correction of the raw phase measurements, and the estimation of the elements of a full covariance matrix for the raw GPS phase data according to the likely size of the multipath contamination and the amount of correlation of errors between satellites.

An alternative to traditional least squares modelling of systematic errors in GPS data has also been proposed. The semiparametric model and penalised least squares method describe multipath by a complex but smoothly varying function with time. The functions, and estimated parameters such as station coordinates and ambiguities, are decomposed using the penalised least squares method. Multipath mitigation using the repeatability of SNR ratios over the sidereal day at permanent GPS receivers is based on using a residual stacking algorithm. Others separate multipath from the carrier phase observations. The University of Colorado has developed an algorithm to utilise the spatially-correlated characteristics of multipath to reduce multipath in ground and space-based applications. This algorithm will be used to mitigate multipath in ground-based GPS reference stations.

Electromagnetic Propagation Modelling for Multipath Analysis

The European Space Agency (ESA) is using a software tool "Multipath Virtual Laboratory" (MVL) to compute multipath effects on the GPS observables having satellite constellation location, receiver antenna location, positioning of surrounding structures and antenna information as input parameters. The computation of signal propagation uses a ray-tracing angular Zbuffer algorithm, followed by an electromagnetic field computation using the Geometric Theory of Diffraction (GTD). The MVL tool was used to pre-compute the presence of multipath for the rendezvous of the shuttle Atlantis with the Russian space station MIR.

Work on modelling the multipath environment of the International Space Station is currently underway at the Jet Propulsion Laboratory (JPL) using a multipath simulator previously developed in 1990. In this recent application of the simulation model, the measurement error due to multipath has been computed for a number of different antenna locations. Once the multipath error for each antenna is computed, the corresponding orbit error due to multipath is determined using JPL's GIPSY-OASIS II orbit determination software.

A relatively new technique that involves a numerical solution to the Parabolic Equation (PE) has been used to solve for two-dimensional propagation over any type of terrain. The PE provides a direct solution of Maxwell's wave equations by approximating the Helmholtz scalar wave equation. This technique does not rely on the study of individual ray paths as used in the GTD. Propagation simulations from the model accurately provide the amplitude and phase of the propagated plane wave at all points within the model domain. The PE model was used to study the effects of diffraction and multipath caused by various types of terrain commonly found in an open cut mining environment.

Multipath Characterisation and Attitude Determination

Both ESA and the NASA Johnson Space Center group have been studying multipath effects on attitude determination in the particularly severe environment of the International Space Station (ISS). NASA has compared space shuttle GPS flight data to predicted results from geometrical diffraction prediction. ESA has analysed data from on-ground experiments and in-flight demonstrations for the rendezvous and docking of ESA's Automatic Transfer Vehicle with the ISS. Researchers at ESA have also studied the design of a modified patch antenna that provides low elevation and LHCP signal rejection. Size, weight, and other characteristics are designed for space applications with the goal of improving attitude accuracy below 1�.

Two academic research groups specialise in multipath mitigation for attitude determination. One group have looked at phase map corrections for using simulations and satellite data from the CRISTA-SPAS Experiment. Another group proposes the use of non-dedicated receivers for attitude determination, including using a group of closely spaced antennas for multipath correction in RTK. Attitude accuracy is quite poor because antenna separation is very small. Multipath reduction with the multi-antenna array has been studied in various environments, such as in urban canyons and under foliage. Improvement due to multipath corrections is reported to be approximately 50%.