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# Differential GPS Measurement of Overhead Conductor Sag: Software Implementation

*Final Project Report*

**Power Systems Engineering Research Center**

*A National Science Foundation  
Industry/University Cooperative Research Center  
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**Power Systems Engineering Research Center**

**Differential GPS Measurement of Overhead  
Conductor Sag: Software Implementation**

Final Project Report

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## Executive Summary

This is a final report on the development and implementation of software that can be used to estimate and continuously display the changing real-time current rating of a transmission-line conductor. The software can be used in an on-line energy management system (EMS) as an aid to power system operators. The software uses information from an instrument that can measure the sag of overhead transmission conductors for 69 kV circuits and above. The instrument may be based on either (1) direct measurement (such as a device that uses a Global Positioning Satellite signal or an optical surveying instrument), (2) an instrumentation system that uses calculation procedures (such as the 'Power Donut', a 'CAT' system that measures conductor tension), or (3) a resistive line near the conductors that effectively measures the electric field. A typical GUI screen is shown in Figure (E.1)

The dynamic thermal real time rating of a circuit is estimated using linear state estimation based on historical data. The historical data are loaded into a least squares estimator, and a model is obtained for the circuit sag as a function of line load and weather parameters. Then, the maximum permissible sag is used to 'work backwards' and calculate the real time current rating of the conductor. Plans are being made to test the software using data from an actual circuit.

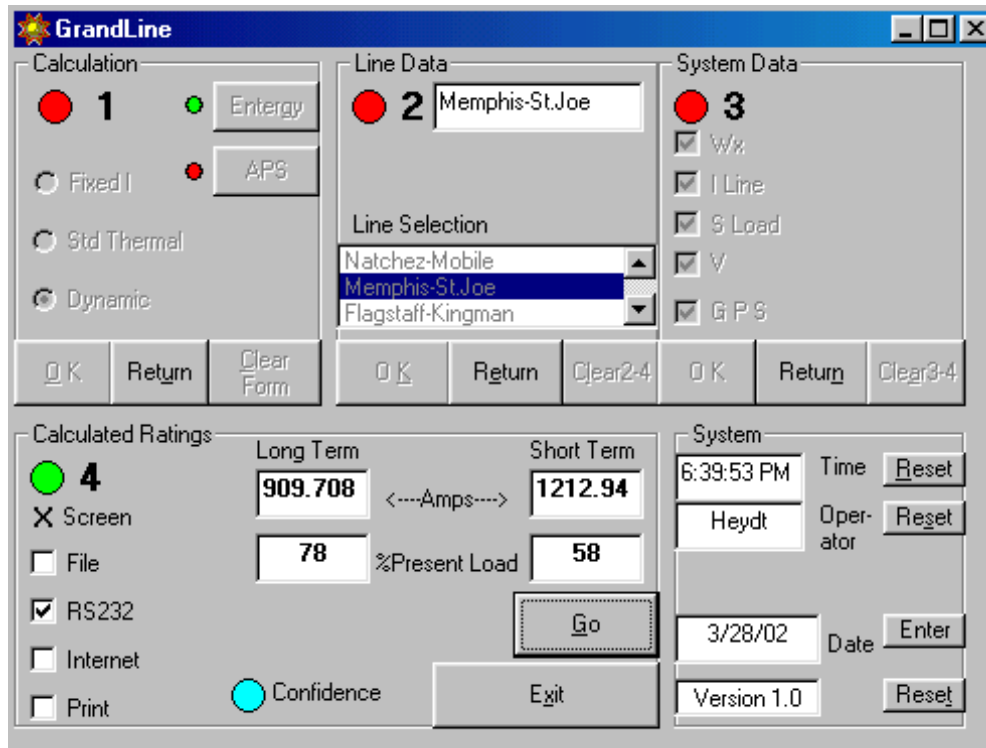


Figure (E.1) Typical graphic user interface for program GrandLine -- to calculate real time overhead conductor sag

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## Nomenclature

ACEPS	Center for the Advanced Control of Energy and Power Systems, formerly an NSF Industry / University Cooperative Research Center
APS	Arizona Public Service
EMS	Energy management system
GPS	Global Positioning System
GUI	Graphic user interface
/	Current
IEEE	Institute of Electrical and Electronic Engineers
LSE	Least squares estimation
rms	Root mean square
PSERC	Power Systems Engineering Research Center, an NSF Industry / University Cooperative Research Center
S	Complex power, MVA; overhead conductor sag data
V	Voltage
VB6	Visual Basic version 6.0
WX	Weather
X	Estimator parameters
Z	Measurement matrix

# **Differential GPS Measurement of Overhead Conductor Sag: Software Implementation**

## **Final Project Report**

### **1. Abstract**

This research project is to develop a graphic user interface for the calculation of the real time rating of overhead electric power transmission conductors. The scope is for 69 kV circuits and higher. The concept is that measurements of sag of the conductor are used in connection with a linear state estimator to predict the circuit rating in real time. The input of the estimator is the real time sag of the conductor, the weather (wind velocity, wind direction, ambient temperature, circuit current, and real time sag measurement). The estimator output is the real time circuit rating in amperes based on a maximum sag allowance.

The sag measurement used as an input to the estimator may come from a tension monitor device, from an optical measurement, from a Global Positioning System (GPS) based instrument, or from a device that measures the electric field in the vicinity of the conductors.

The objective is to give the system operator a real time circuit rating in a convenient form - using a graphic user interface (GUI).

Examples of the software are given in the report to illustrate the capability of the GUI and the estimator used for the calculation.

### **2. Research need and applications**

The objective of this project is to utilize measurements of overhead conductor sag and to use this device in an on-line energy management system (EMS) aid to operators. The work is implemented in software, including a visual graphic depiction for easy use.

### **3. Research project team**

The research project team consists of G. T. Heydt of Arizona State University and Robert Olsen of Washington State University. Some industrial input was obtained from Mr. F. Galvan of Entergy in New Orleans and Mr. J. Schilleci also of Entergy. Dr. Baj Agrawal of Arizona Public Service also provided input to the project and Mr. D. Selin of Arizona Public Service also helped on project definition. The assistance of Professor R. Farmer is also acknowledged.

This project built on a previous PSERC project relating to the design of a GPS instrument to measure overhead conductor sag [1-3, 5]. Dr. C. Mensah-Bonsu of the California ISO worked on that project. A summary of the previous work appears in Appendix C.



#### **4. Project duration**

The project started in May 2002 and is scheduled to end in December 2002.

#### **5. Project description**

In 2000, an ACEPS project promoted mainly by Entergy and APS developed a Global Positioning System in which differential GPS technology is used to measure the vertical position of the lowest point of overhead transmission conductors [1-3, 5]. The work resulted in a PhD thesis, report, and IEEE Transactions paper. The present work represents an extension of the GPS instrument project in which real time sag data and real time circuit loading are processed to find the real time circuit rating. This is the real time, thermal current rating of the line, including effects of wind and solar radiation.

#### **6. Potential benefits**

The GPS based sag measurement device is expected to give an alternative to the load cell and other methods for conductor sag measurement. These other technologies have their own drawbacks and advantages. In some applications, the GPS technology may be a more affordable means of deriving real time current rating.

The advantage of real time current ratings relates to the utilization of overhead conductors to their fullest. In this way, thermally limited systems may be more heavily loaded. Quantitatively, thermally limited systems might often be loaded about 30% more (depending on weather and operating conditions). The increased utilization translates to higher available transfer capability.

#### **7. Main product of the project: program "GrandLine"**

The main product of the project is a Visual Basic 6.0 platform for reading real time GPS data from overhead conductors, and reading weather and selected historical EMS data. The software can calculate and display (or output) real time current ratings for overhead conductors.

The program developed is named GrandLine. The main inputs and outputs are listed in Table (7.1). The graphic user interface developed is described in Section 9 of this report.

**Table (7.1) Main inputs and outputs of program GrandLine**

<i>Inputs</i>	<i>Outputs</i>
Weather data (wind velocity, direction, ambient temperature, time stamped)	Percent line load
Line loading (current, MVA)	Line rating (real time, thermal, table lookup)
Line voltage	Operator information
Type of line rating required	Time of day
Line data format (APS, Entergy)	Date
GPS sag measurement	GrandLine version (presently 1.0)
Output data medium	
Transmission line data (length, designator, resistance, reactance, charging, terminals)	

## 8. Technical Approach

The technical approach of the project consists of three main areas: differential GPS technology, state estimation, and visual graphic presentation. The differential GPS technology makes use of the contemporary GPS system in place. The system has vertical positioning error in the order of 3 m in the simple raw data mode. If a GPS derived vertical position is available from a surveyed site, a differential correction may be derived and applied to a 'rover' GPS placed on an overhead conductor. In this way, differential GPS is used to drastically reduce measurement error. Also, several state estimation methods (e.g., weighted averaging) can be used together with bad data rejection to further reduce measurement error. Laboratory demonstrations for this project have shown less than a 17 cm expected vertical position error.

The present project is for implementing the differential GPS based instrument with software. The theoretical approach is to continue the state estimation work and implement this in Visual Basic 6.0. An object oriented approach and visual graphic technology are used to read the GPS data (as well as weather and historical current loading data), calculate the real time conductor rating, and effectively display the results in a graphic user interface.

The essence of the software developed is the following:

- Establishment of a Visual Basic shell to read time series data recorded from sag instruments
- Utilization of linear state estimation to fit a multi-point nonlinear model to the measured sag and measured circuit loading. Weather data are also included in the model. The estimator is used to find the circuit loading (amperes) to produce maximum sag.
- Development of a user-friendly output medium for the calculated current rating.

The software developed for the Visual Basic shell and the output medium is documented in the Appendix A. The state estimator theory is documented in Appendix B.

## 9. The graphic user interface

The main output of the program GrandLine is the graphic user interface. A typical GUI is shown in Figure (9.1). The GUI is divided into four numbered panels and a fifth sector which gives logging information. The function of the four numbered panels is tabulated in Table (9.1). Table (9.2) lists the descriptors and functions of the remainder of the GUI. The main features of the GUI are:

- Four input panels
- Link to Microsoft Access data files
- Files in distinctive data format (e.g., Entergy, APS)
- Input data selectable
- Output medium selectable.

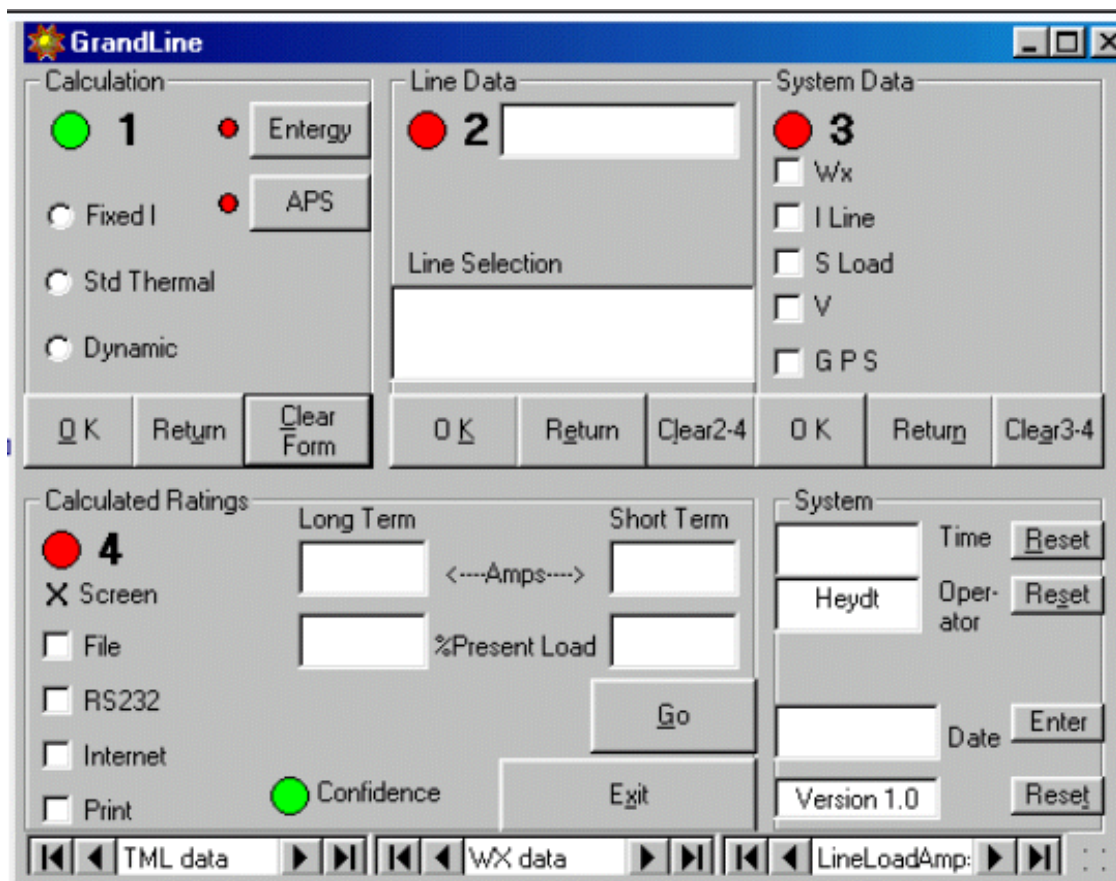


Figure (9.1) GrandLine GUI

**Table (9.1) Panel functions in the GrandLine GUI**

Panel	Descriptor	Functions
1	Calculation	This panel inputs the type of calculation to be done. The choices are fixed current ratings (i.e., table lookup for the conductor in question); standard thermal rating calculation; and dynamic rating calculation. Also input are the data format types (presently listed as APS and Entergy formats).
2	Line data	This sector selects the line to be evaluated.
3	System data	This panel selects and links the several possible types of input data. The choices are: line current measurements, line MVA measurements, voltage, and GPS derived sag data.
4	Calculated ratings	This panel selects the output medium (in addition to the GUI itself). The output choices are: to a specified file; via RS323; via the Internet at a specified URL; and to a printer. The panel also is the venue of the output calculation, both long term and short term. The present line loading is shown as a percentage of the calculated rating. Red and yellow are used to color the output data windows to flag overload and near overload conditions. A confidence level indicator is used in a chi-squared test for the state estimation.

**Table (9.2) Sector descriptors and functions of the GrandLine GUI**

Panel	Descriptor	Function
Lower segments for file selection	TML data; WX data; line load ratings	These are file selectors that interface with databases. The present GrandLine format is the use of Microsoft Access databases. The databases correspond to transmission line data, weather data, and published line load ratings of the lines.
Lower right ("fifth") panel	System	The system panel describes the following: the time of day; the operator; the date; and the version of GrandLine.

Figure (9.2) shows the GUI in operation. Figure (9.3) shows a line selected. Figure (9.4) shows the rating procedure for the use of section (panel) 4. Figure (9.5) shows the final stage with line ratings indicated. In Figure (9.5), no line currents are above rating. Lines above rating are flagged in red as shown in Figure (9.6).

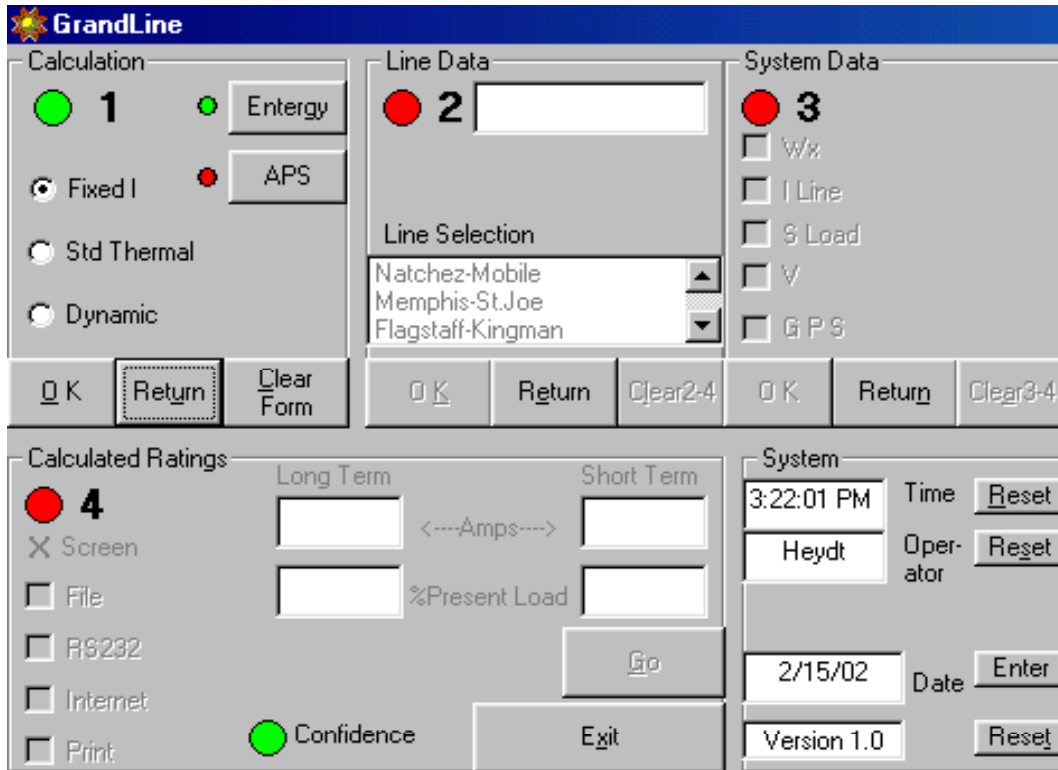


Figure (9.2) GrandLine GUI showing typical operation

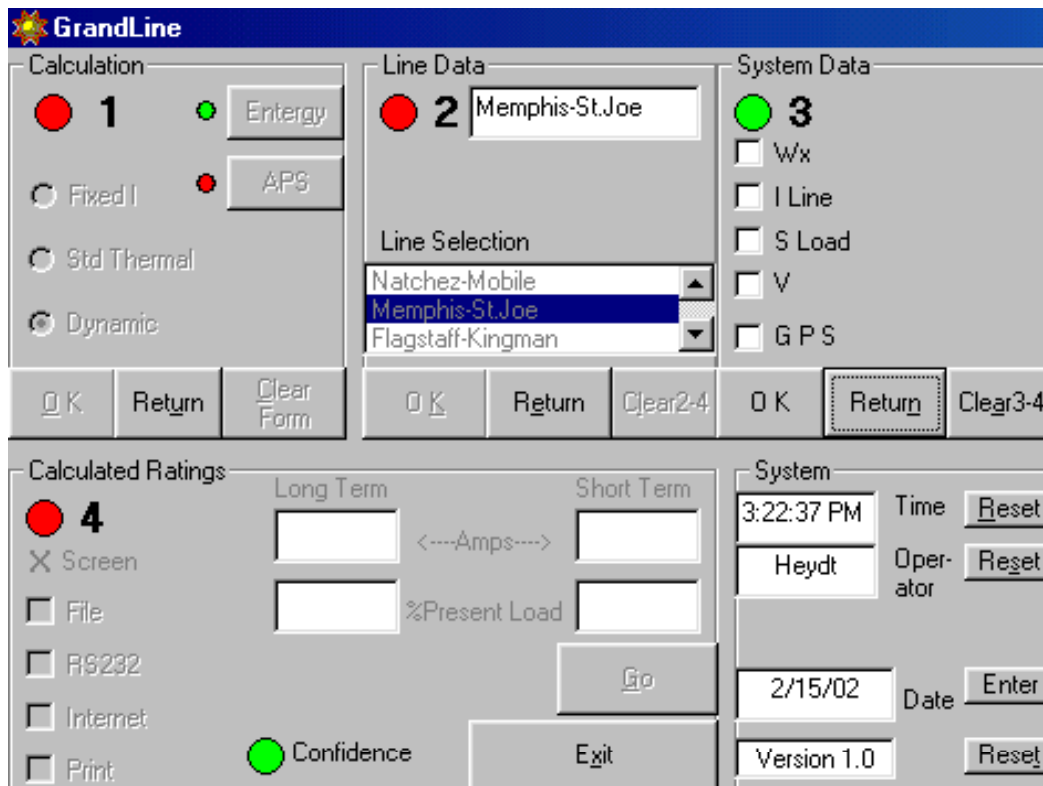


Figure (9.3) GrandLine GUI showing line selected

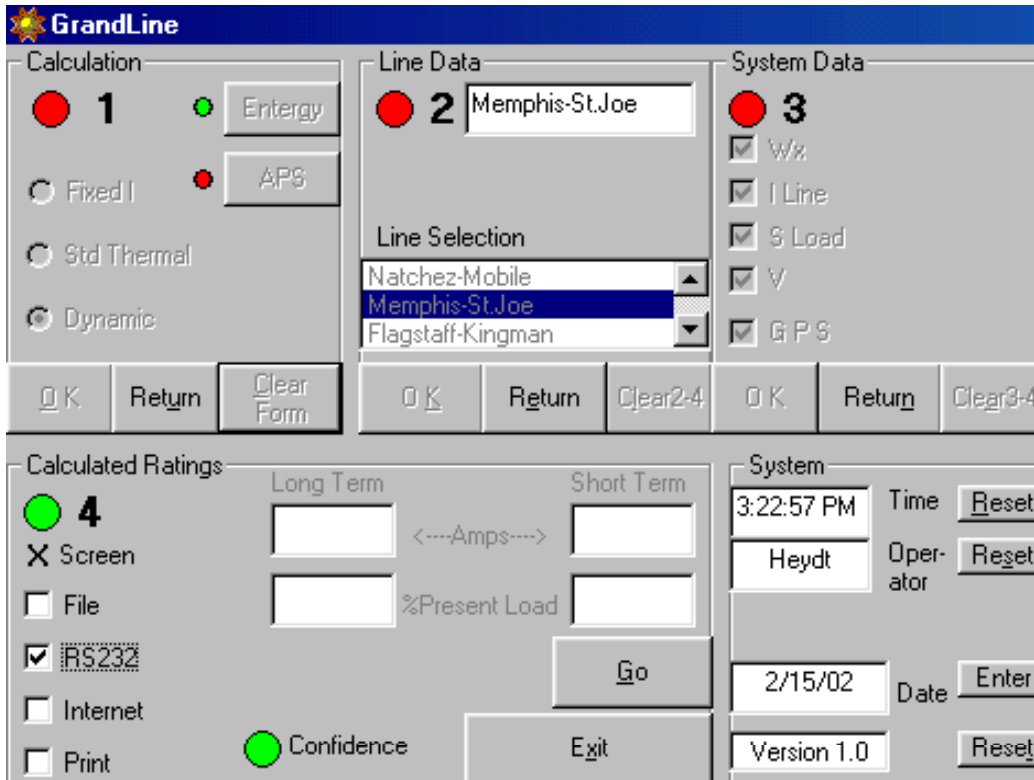


Figure (9.4) GrandLine GUI showing panel 4 in use

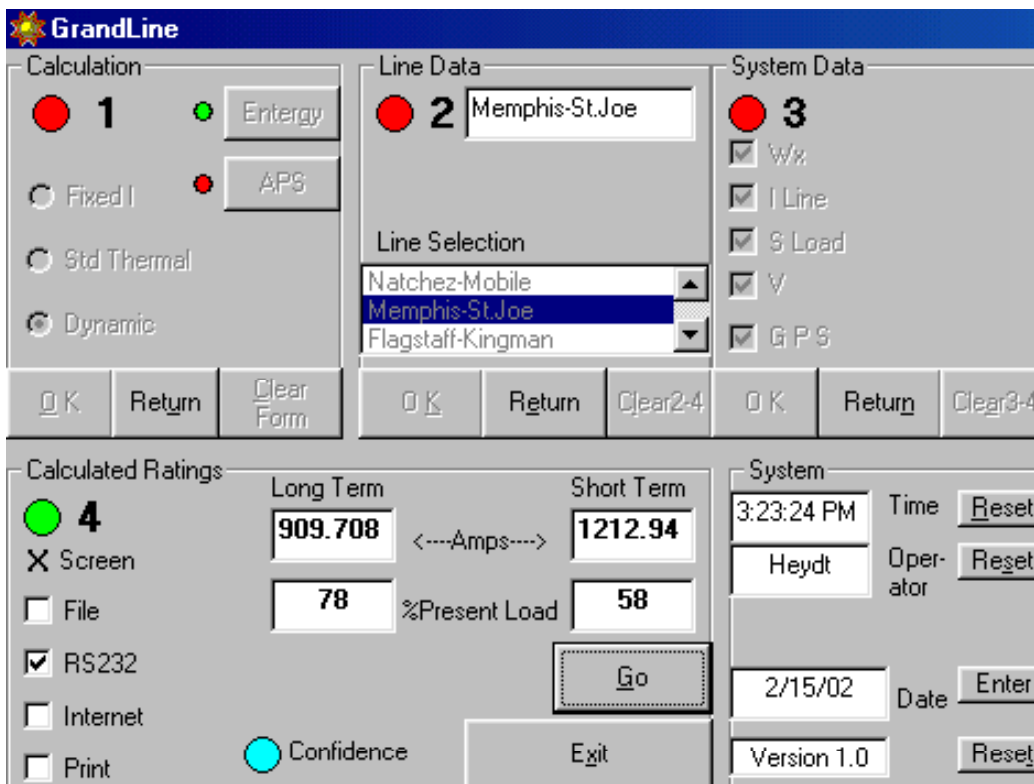
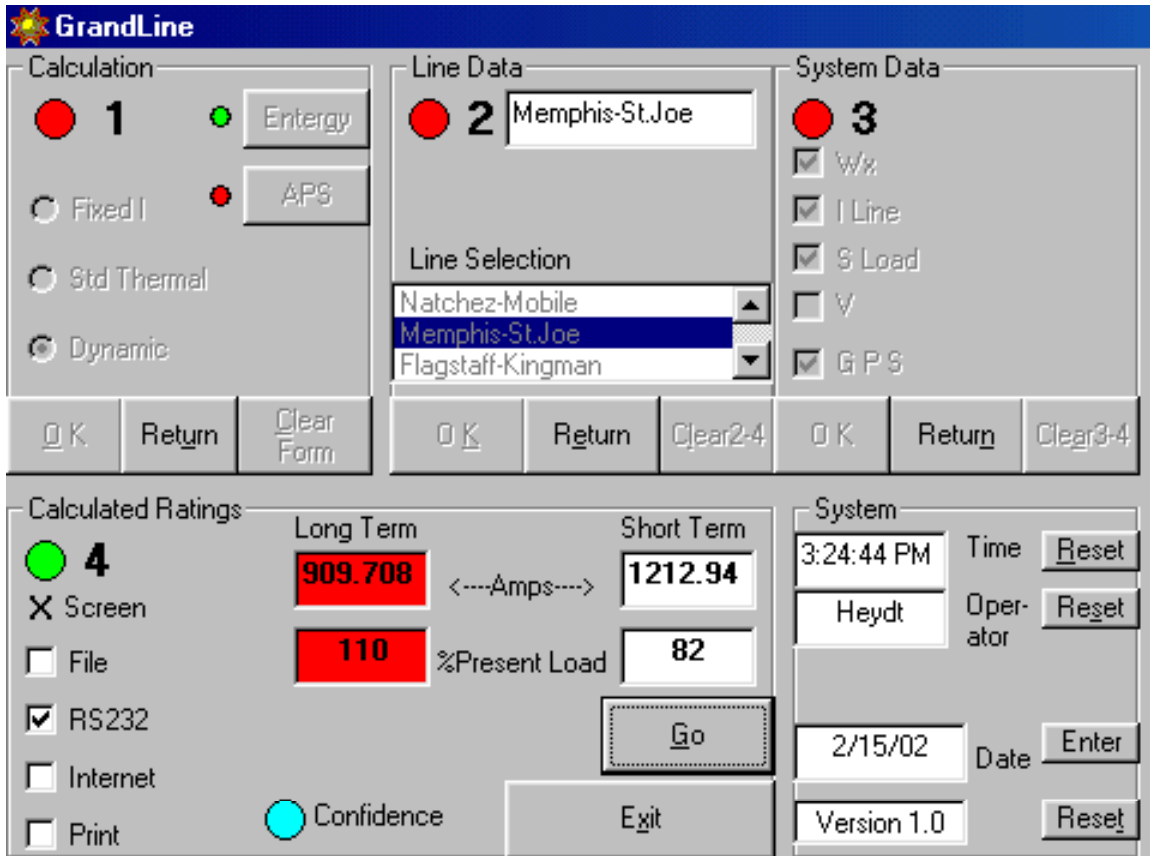


Figure (9.5) GrandLine GUI showing line ratings



**Figure (9.6) GrandLine GUI showing line current above ratings - flagged in red**

## 10. Related work

The related work in real time thermal rating of overhead transmission conductors and their relationship to the present project are [3, 4]:

- Classical real time rating methods: these have been theorized for at least ten years with few implementations. One technology uses only present weather data to estimate real time current rating. The advantage is simplicity; the disadvantage is poor accuracy. The conductor sag is not measured directly. In [2] a full description of classical methods is given.
- Load cell measurements: this is a commercialized technology that has advantages of experience and off-the-shelf availability. Disadvantages include cost, and inconvenient installation. In this technology the sag is calculated and not measured directly.
- 'Power donut measurement': this is a commercialized technique in which conductor temperature is measured by thermistor contact. This is also a commercialized technology that has advantages of experience and off-the-shelf availability. The power donut may be used to instrument voltage and current. The disadvantages are that sag is not measured directly, potentially high cost, and there have been reported problems with communications. In [2] gives photographs and circuits used for the power donut.

The key difference of the proposed technology is that overhead conductor sag is measured directly rather than by calculation. Also, the presently proposed work includes a graphic user interface and state estimator that has not been developed or demonstrated elsewhere. The significance of these advancements is accuracy and ease in use. Also, the GPS technology overall is potentially much cheaper than existing technologies.

## 11. Conclusions and recommendations for implementation

The main conclusion of the present project is that it is possible to estimate with high accuracy the dynamic rating of transmission lines using state estimation and historical data. Direct or indirect measurements of sag are needed in the line historical data. A GUI has been demonstrated as an effective way to present the line rating data to operators.

The next step in this research is to install an actual unit in the field. The details of the recommendation are given in Appendix D.

## 12. References

[1] C. Mensah-Bonsu, G. Heydt, "Overhead Transmission Conductor Sag: A Novel Measurement Technique and the Relation of Sag to Real Time Circuit Ratings," *Journal of Electric Power Components and Systems*, accepted for publication, 2002.

[2] Chris Mensah-Bonsu, *Instrumentation and Measurement of Overhead Conductor Sag using the Differential Global Positioning Satellite System*, PhD. Thesis, Arizona State University, Tempe AZ, August 2000.

[3] C. Mensah-Bonsu, U. Fernández, G. T. Heydt, Y. Hoverson, J. Schilleci, B. Agrawal, "Application of the Global Positioning System to the Measurement of Overhead Power Transmission Conductor Sag," *IEEE Transactions on Power Delivery*, vol. 17, No. 1, pp. 273-278, January 2002.

[4] R. G. Olsen, K. S. Edwards, "A New Method for Real-Time Monitoring of High Voltage Transmission Line Conductor Sag," submitted in 2002 to the *IEEE Transactions on Power Delivery*.

[5] G. T. Heydt, *The Development of a Graphic User Interface for an Overhead Conductor Sag Instrument: Final Project Report*, PSERC Publication 02-24, April 2002.



## Appendix A

### Software Description

#### A.1 Capabilities of Visual Basic 6.0

Visual Basic 6.0 is a graphic computer language that is used to develop object oriented programs. These are programs that are popularly known as menu driven programs, and they involve menus, pull-down tabs, command buttons, and many other graphic devices that appear on the CRT screen. Examples are Microsoft Word and Microsoft PowerPoint. The language is similar to Visual C++, Visual J++, and some other graphic languages.

A Visual Basic 6.0 program is made up of code, and the code is broken into procedures, assignments, commands, and lower syntax forms. The main elements are procedures that are basically subroutines.

Although Visual Basic 6.0 is an outgrowth of Basic, Visual Basic 6.0 differs dramatically from the Basic language of 20 years ago. Visual Basic 6.0 is a sophisticated language that is powerful, is highly integrated with C, C++, Visual C++, and Java related languages. That is, it is easy to import subroutines from these languages to Visual Basic 6.0. In fact, the syntax of Visual Basic 6.0 and the other cited languages is rather similar. In addition to the integration of these languages, Visual Basic 6.0 can access a range of Microsoft products such as Excel and Access. That is, data in many other Microsoft products can be imported into Visual Basic 6.0 with a single simple syntax statement.

A main advantage of Visual Basic 6.0 is the ease in which complex forms (i.e., menus) can be generated. Professional forms are possible by a drag-and-click technique: programming is mainly using a selection procedure that involves drag-and-click operations. It is also possible to program in the usual way by entering syntax line by line.

Perhaps the main disadvantages of Visual Basic 6.0 are the long length of typical programs, relatively inconvenient procedures needed to run compiled programs on computers that do not have Visual Basic 6.0 installed, and the fairly strong commitment to Microsoft Access as a database language. All these problems are relatively minor, and no true special skills are needed to obtain very good results. It is conjectured, however, that a dedicated professional programmer would be needed to develop production grade Visual Basic 6.0 software.

The subsequent section contains a small sample of code in Visual Basic 6.0. The sample is part of the code used to generate the forms used in the body of this report.

## A.2 An example of the code used to generate the Visual Basic GUI for sag monitoring / processing (Program GrandLine)

The prototype software developed for this project is called GrandLine. The following is the main module of the Visual Basic 6.0 software for GrandLine.

```
Private Sub Form_Load()  
,  
'Rating types  
,  
'Fixed I  
'Fixed I rating comes from tabular values for that conductor  
,  
'Standard Thermal  
'Standard thermal ratings come from the data  
'sheet for that conductor as recorded in the  
'TML database  
,  
'Dynamic  
'The dynamic rating comes from a calculated sag  
'versus line loading for the conductor versus  
'time. The parameters of the sag are estimated  
'using a LSE and the maximum long and short term  
'current are calculated. GPS data must be used for this calculation.  
,  
*****  
' Required Attached Data Bases  
,  
'PresLineLoadAmps.mdb Present line load in amps  
,  
'WX.mdb Present weather  
,  
'TML3.mdb Transmission line data  
,  
*****  
"Set up initial settings  
,  
'Frame 1  
shp1Calculation.FillColor = &HFF00& 'Green  
boolEntergy = False  
boolAPS = False  
'set APS/Entergy indicator lights  
shp1Entergy.FillColor = &HFF& 'Red  
shp1APS.FillColor = &HFF& 'Red  
cmd1APS.Enabled = True  
cmd1Entergy.Enabled = True  
,  
'Frame 2  
shp2LineData.FillColor = &HFF& 'Red  
cmd2OK.Enabled = False  
cmd2Return.Enabled = True
```

```

cmd2Clear24.Enabled = False
lst2Lines.Enabled = False
'
'Frame 3
shp3SystemData.FillColor = &HFF& 'Red
cmd3OK.Enabled = False
cmd3Return.Enabled = True
cmd3Clear34.Enabled = False
chk3Wx.Enabled = False
chk3Line.Enabled = False
chk3SLoad.Enabled = False
chk3V.Enabled = False
chk3GPS.Enabled = False
'
'Frame 4
shp4CalculatedRatings.FillColor = &HFF& 'Red
chk4File.Enabled = False
chk4RS232.Enabled = False
chk4Internet.Enabled = False
chk4Print.Enabled = False
lbl4X.Enabled = False
lbl4Screen.Enabled = False
cmd4Go.Enabled = False
lbl4LongTerm.Enabled = False
lbl4ShortTerm.Enabled = False
txt4Rating.Enabled = False
txt4ShortTerm.Enabled = False
txt4LTLoad.Enabled = False
txt4STLoad.Enabled = False
lbl4Amps.Enabled = False
lbl4PctLoad.Enabled = False
txt4Rating.Text = ""
txt4LTLoad.Text = ""
txt4ShortTerm.Text = ""
txt4STLoad.Text = ""
txt4LTLoad.BackColor = &HFFFFFF 'White
txt4STLoad.BackColor = &HFFFFFF 'White
txt4Rating.BackColor = &HFFFFFF 'White
txt4ShortTerm.BackColor = &HFFFFFF 'White
shp4Confidence.FillColor = &HFF00& 'Green

'Frame 5
Dim theTime As Date
theTime = Time
txt5Time.Text = theTime
Dim dtmDate As Date
dtmDate = Date
txt5Date.Text = dtmDate
'
'Pseudoinverse and on-line state estimator
Dim nunks As Integer
Dim nequs As Integer

```

```
'Estimator parameters  
nequs = 22  
nunks = 11  
,  
,  
End Sub
```

## Appendix B

### Linear State Estimation for Calculating Maximum Circuit Loading of Overhead Conductors

Most physical processes can, in the short term, be represented as a polynomial series of the independent variables measured at the instant of interest and past values. In this instance, the physical sag of an overhead transmission line,  $s$ , can be expressed in terms of the instantaneous and past values of:

Wind speed component perpendicular to the line =  $w_s(t), w_s(t-h), w_s(t-2h), \dots$

Circuit load current =  $i(t), i(t-h), i(t-2h), \dots$

Past sag values =  $s(t-h), s(t-2h), \dots$

where  $h$  is the time interval of the measurements, and the past measurements are carried out sufficiently to capture the physical dynamics. In general, the past history to about 15 minutes is sufficient thus reflecting the thermal time constant of an overhead transmission conductor. Typically,  $h$  is approximately one minute. If a linear combination is used, the instantaneous sag of a conductor is

$$s(t) = a_0 w_s(t) + a_1 w_s(t-h) + a_2 w_s(t-2h) + \dots + b_0 i(t) + b_1 i(t-h) + b_2 i(t-2h) + \dots + c_1 s(t-h) + c_2 s(t-2h) + \dots \quad (\text{B.1})$$

If a large number of past readings of sag are available, the left side of Equation (B.1) can be arranged in a vector  $S$  with the top row as the present sag (read from any kind of instrument); and the right hand side of (B.1) as an array of unknown coefficients (i.e., the  $a$ ,  $b$ , and  $c$  terms) arranged in an unknown coefficient vector  $X$ ; and the known measurements (i.e., the  $w$ ,  $i$ , and past  $s$  terms) arranged in a known measurement matrix  $Z$ . Then Equation (B.2) becomes

$$S = ZX \quad (\text{B.2})$$

The form of Equation (B.2) is well known; this is many equations in relatively few unknown  $X$  values. The 'solution' is found by a method known as 'least squares', and this is written as

$$X' = Z^+ S = (Z^t Z)^{-1} Z^t S. \quad (\text{B.3})$$

In Equation (B.3), the notation  $( )^+$  refers to the pseudoinverse of a matrix; the prime on  $X$  refers to the fact that the formula (B.3) is an estimate; and  $( )^t$  refers to the transpose of a matrix. The formula (B.3) is an estimate because Equation (B.2) is an overdetermined set of equations: that is, there are more equations than unknowns in (B.2), and there is no exact solution to (B.2). When there are many more equations than unknowns, and when the problem is well formulated, the estimate occurs with high confidence.

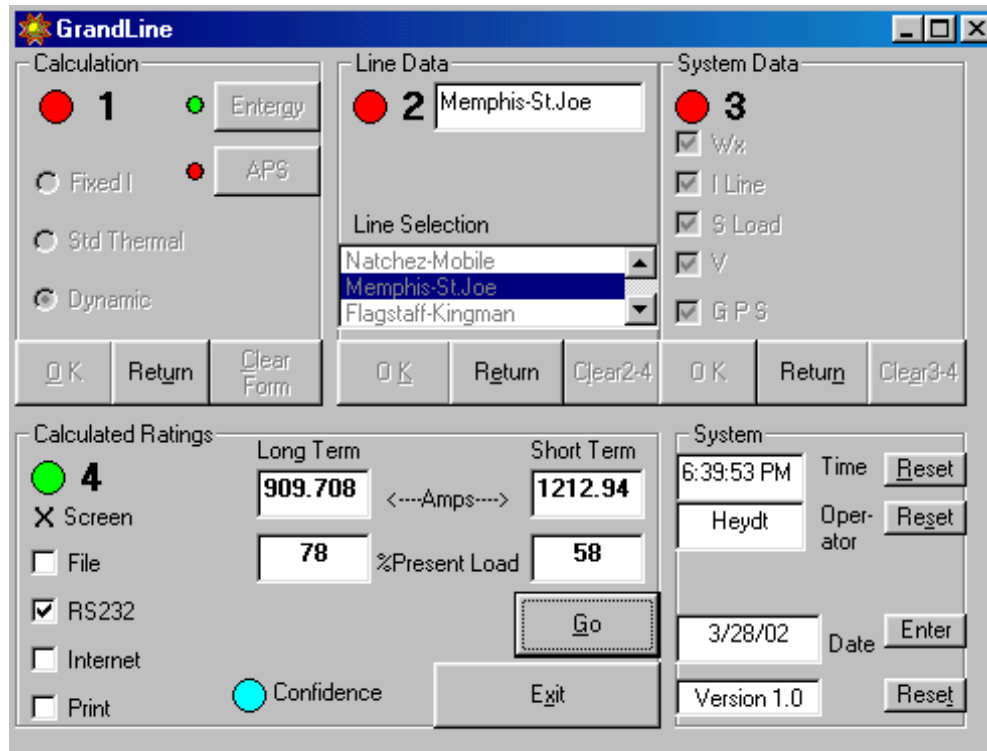
Note that the confidence in the estimate (B.3) is easily found by evaluating the residual  $R$ ,

$$R = | ZX' - S |$$

That is, the residual  $R$  is simply the norm of the difference of the right and left hand side of Equation (B.2).  $R$  is a measure of how well  $X'$  fits the equations. If  $R$  is large, the error is large, and there is low confidence in the solution.

In a typical formulation, the dimensions of the matrices and vectors are: measurements  $Z$  is about 44 by 50 (i.e., 15 wind speeds, 15 currents, and 14 sags over 50 past readings);  $X$  is about 44; and  $S$  (past sags) is about 50. The residual  $R$  is a scalar.

The expression (B.3) and the residual formula have been programmed in Visual Basic 6.0. The pseudoinverse is carried out using the Shipley Coleman method for matrix inversion. The software was attached to synthetic data generated only for this prototype. The result is illustrated in Figure (B.1). The calculation is done virtually instantaneously in the prototype. The confidence is depicted in section 4 of the graphic user interface as a colored circle: green for high confidence, yellow for caution, and red for low confidence. In theory, this GUI can get attached to data from any sag instrument. The only requirement is that the software must be able to read the data format.



**Figure (B.1) A graphic user interface for the calculation of a real time rating of an overhead transmission circuit based on sag**

## Appendix C

### Summary of Previous Work

#### C.1 Introduction

This appendix contains the main points of a project completed in 2000 on the design of a GPS instrument to measure overhead conductor sag [1-3, 5].

#### C.2 Concept of a GPS instrument to measure conductor sag

The concept of the proposed instrument is the use of differential global positioning technology or DGPS to minimize intentional and unintentional error in the GPS measurement of the position of an overhead transmission conductor. The basic configuration is shown in Figure (C.1). The reasons for the direct measurement of conductor sag are: on-line measurement of the sag; potential utilization of sag data to develop dynamic line rating; potential integration with the Open Access Same Time Information System, an on-line, Internet based system for the sale of transmission capacity. The main advantages and disadvantages of this instrumentation system are listed in Table (C.1).

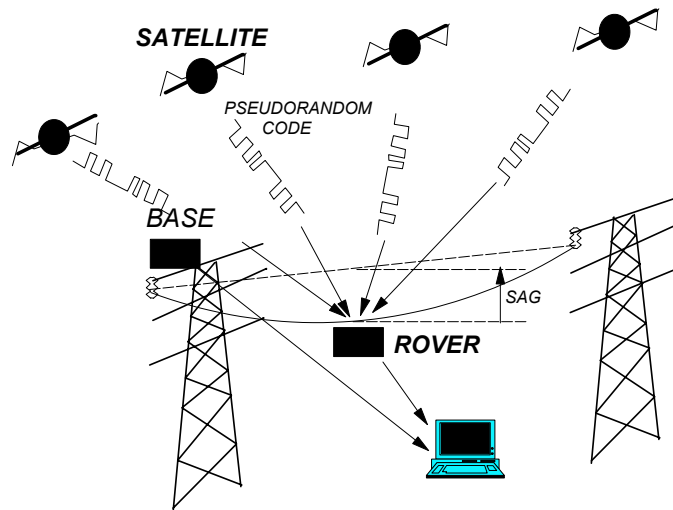


Figure (C.1) Conceptual pictorial of a differential measurement of a conductor sag

**Table (C.1) Advantages and disadvantages of a GPS based measurement of overhead transmission conductor sag**

<i>Advantage</i>	<i>Disadvantage</i>
Cost may be lower	Unknown effects of corona on required communications systems
Accuracy potentially high and better than other technologies (e.g., less than 13 cm errors)	Need to bridge the gap between laboratory development and commercialization
On-line capability measurement of sag in real time (i.e., one measurement per second)	Unknown firm cost figures
The GPS technology is a digital technology, and resultant data is already in digital form.	Packaging of final instrument is problematic.

The following describes the main contributions of the project: a new innovative concept of using a precision DGPS to directly and accurately measure the overhead conductor sag in real time has been proposed for the first time in the history of overhead conductor sag measurements. The essence of the idea is to use the DGPS technology to obtain signals that can be used to find overhead conductor sag and thereby derive circuit ratings. This is to be used in conjunction with known operating point to find the dynamic ratings of the overhead conductor and to determine the optimal operating strategy.

DGPS measurements have been taken and the results seem to validate the goal of the project at hand. Based on the data observations it is evident that the GPS measurement data imitates a standard normal (Gaussian) distribution curve. This property forms the basis for the bad data rejection in the signal processing algorithm. Furthermore, the raw DGPS measurement accuracy in the vertical (z) direction has been enhanced using classical digital signal processing techniques such as bad data identification and rejection, least squares parameter estimation (LSE), artificial neural network (ANN) and hybrid ANN-LSE.

The main conclusion of this study is that DGPS technology is feasible for the direct instrumentation of overhead power conductor sag measurement. The accuracy of such an instrument used has been enhanced to an index range of 19.6 cm in 70% of the time (or even better at reduced percentage levels) by the use of innovative signal processing techniques.

Initial design to allow the instrument (especially the rovers) to acquire operating power from the overhead power transmission conductor has been done and so are the communication links for possible data and information transfers. It is to be noted that a great deal of care must be taken in the design of the instrument package because of the potential possibility of interference from corona discharges.

Although detailed computations relating to dynamic line ratings which is a major integral part of future work of this research project has not yet been considered, it is believed that real time DGPS sag measurement can be translated into real time (dynamic)



circuit ratings. This is expected to have obvious pecuniary value in the sale of transmission capacity as well as providing increased reliability of transmission circuits.

This new approach of measuring the overhead conductor sag, outlined in this project, avoids the direct dependence of temperature, tension and weather condition measurements. Thus, the net result of the overhead conductor sag measurement incorporates the combined effects of weather conditions, the conductor loading in terms of electric current, and all other effects that are difficult to measure individually. This is a potential source for cost reduction and better accuracy in the conductor sag measurement. The real time sag monitoring system described here is hoped to more accurately determine overhead conductor sag and hence, provide reliable clearance capability information. By this approach system operators can have direct access to actual conductor sag and reliable clearance warning information. The main advantage of the concept is that this is a direct measurement of a parameter needed for operation of the transmission facility. The digital signal processing required is described in detail in a four level configuration. Typical accuracy, response time, problems, strengths and weaknesses of the method are also described. Table (C.2) shows a brief summary of the main conclusions.

**Table (C.2) Brief summary of the main conclusions of previous research projects**

<i>Task</i>	<i>Comment</i>
Innovative overhead conductor sag measurement using precision DGPS instrument is proposed	First of its kind in the utility industry
DGPS measurements have been taken.	Measurements validate the feasibility of the research project.
Classical digital signal processing techniques (bad data rejection, LSE, ANN and hybrid ANN-LSE) has effectively been used.	Enhances overhead conductor sag accuracy in the vertical direction
Accuracy achieved	19.6 cm and 37.4 cm in 70% and 90% of the time respectively
Initial design of power supply and communication links	Are already in place
Impact of the technique in OASIS is outlined	Method has immediate promising benefits in the deregulated power market in terms of pecuniary and reliability considerations.
The direct measurement of conductor sag incorporates the combined effects of all difficult to measure parameters.	Potentially cheaper cost and better accuracy since no need to directly measure conductor tension, temperature and weather conditions.
Typical accuracy, response time, problems, strength and weakness of the method are elaborated upon	These are described for the benefit of transparency in comparisons with existing methods.
Reliability of DGPS data	Must be reliable under normal operations of the overhead power conductor on which the rover is located

The main challenges remained to be solved in this respect (prototype construction, packaging and testing) for a successful project implementation can be expanded in the directions as shown in Table (C.3).

**Table (C.3) Future work for project implementation**

<i>Tasks</i>
• Further DGPS data analysis using wavelet techniques
• DGPS device packaging including integration of communication links
• Continuous power supply to the DGPS rover receiver is to be derived from the same HVAC transmission line on which the receiver is located.
• Corona and other characteristics such as electromagnetic field strength and their effects on the normal operation of the DGPS devices
• Communication links for the entire system
• Packaged-prototype testing in an energized environment
• Measurements accuracy evaluation of the overall integrated prototype device
• Develop a simple and reliable algorithm to convert conductor sag data to available incremental conductor rating in amperes or MVA

## **Appendix D**

### **The Development and Demonstration of a Resistance Wire Method for the Measurement of Overhead Transmission Line Conductor Sag**

#### **D.1 Recommendation for future work**

This is a recommendation for research and a demonstration of a concept for the real time measurement of overhead power transmission conductor sag. The concept builds on work already done at Washington State University and Arizona State University [4]. The recommendation is made as a result of research on previous research projects. The basic instrumentation method is based on a measurement of the electric space potential integral along a catenary curve in the vicinity of a three phase high voltage line. If the catenary is located correctly, this integral is small due to a cancellation effect of the three phase conductors and very sensitive to changes in sag. An innovative method for measuring this space potential integral is to measure the current induced on a resistive wire near the conductors.

The main points of work reported in [4] are summarized in this appendix.

#### **D.2 Motivation and scope of recommendation**

The motivation of this recommendation is to improve line loading capability by real time measurement of overhead line conductor sag using a resistive wire. The technique is conceptually simple, and has the potential of an easily implemented, low cost technology for the measurement of conductor sag.

The scope of the recommendation includes the development and demonstration of a system for real time overhead sag measurement and calculation of line ratings, including digital signal processing and graphic user interface by measuring induced currents in a resistive wire near three phase transmission line conductors.

#### **D.3 Recommended research and testing**

The recommendation is to demonstrate the concept of resistance wire measurement of overhead conductor sag in an approximately one week demonstration. Ideally, the transmission line used for the experiment will have either a vertical or delta configuration. However, if only horizontally configured lines are available, the test can still be performed. Although, initial testing was done on a 115 kV transmission line, the voltage class is not limited and a higher voltage line could be used. The demonstration will include several alternative measurement / instrumentation techniques to determine the best methods. Digital signal processing (DSP) of the recovered data shall be applied. The DSP shall include estimation of the real time circuit rating using the method of least squares. The data shall be brought to a suitable database for a graphic user interface and estimation of the real time line rating (based on conductor sag).

The recommended work is related to three specific recent research projects. These projects are described below.

*A. A new method for real-time monitoring of high voltage transmission line conductor sag (funded by Avista) [4]*

In 2000, Avista funded a project at Washington State University to develop and test a simple and inexpensive method to measure transmission line conductor sag using a measurement of the current induced on a resistive wire. From this measurement it is possible to accurately calculate the average conductor core temperature. As shown in Figure (D.1), two ends of a grounded wire with relatively high electrical resistance are attached to appropriate locations on each of two transmission line structures and the current induced on the wire by the nearby transmission line conductors is measured.



**Figure (D.1) 115 kV line with resistive wire installed between the conductors**

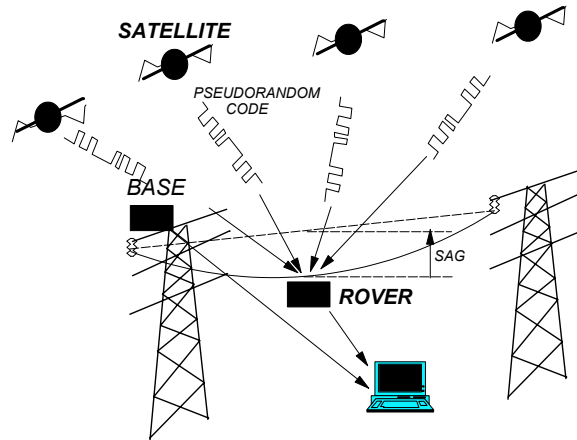
If the system is designed to be maximally sensitive to the sag, it was shown that changes in sag of less than 1% of the span length changed the measured current by a factor of 10. As a result, sag changes of 6 inches are easily measured.

*B. The use of the Global Positioning System (GPS) to measure the sag of overhead conductors (Funded by Entergy) [1-3, 5]*

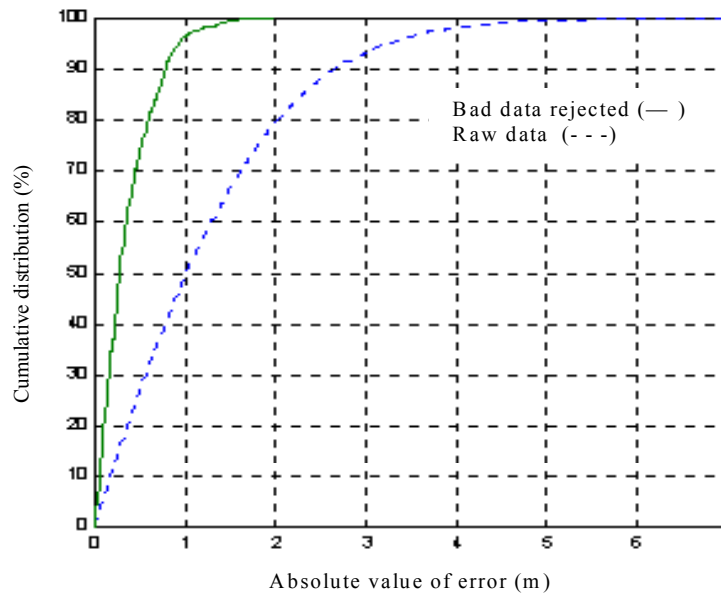
In 2000, Entergy funded a pilot project for the development of an instrument that uses the GPS to measure sag. The basic concept is depicted in Figure (D.2). The project resulted in the design of a prototype instrument that was tested at low transmission line power. The device uses a low power differential GPS receiver plus a spread spectrum transceiver to form a differential GPS instrument. One of the two GPS receivers in the differential configuration is located on the transmission line. The altitude reading of the remote GPS is reported to a base station receiver where digital signal processing and correction is done. In a laboratory environment, the instrument produces 17 cm error or less 70% of the time. Figure (D.3) shows the distribution of error in GPS instru-

mentation in this application. The cost of the unit is mainly the packaging cost of the GPS instrument on the transmission line. The differential GPS receivers are relatively low cost. The project ended in 2000 and was reported as:

- IEEE paper [1]
- NAPS paper [2]
- A PhD thesis [3].



**Figure (D.2) Basic concept of a GPS instrument to measure the sag of an overhead conductor**



**Figure (D.3) The cumulative distribution of error in a differential GPS instrument to measure overhead conductor sag**

*C. Development of a GUI for a sag instrument (funded by Entergy and PSERC)*

In 2001, Entergy and PSERC funded a research project on the development of a graphic user interface (GUI) and estimation software package for the depiction of sag data, and calculation of real time conductor rating [5]. The project GUI, developed in Visual Basic 6.0 appears to give the kind of information that an operator may desire in a graphical sense. The software can be connected to any suitable database written as a text file or as a standard database (e.g., Microsoft Access). The project ended in December 2001, and the software is available as an engineering prototype.