

# *GPS Surveying - System 300*

## ***A Network of Real-Time GPS Reference Stations for a Major Civil-Engineering Project***

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## **Abstract**

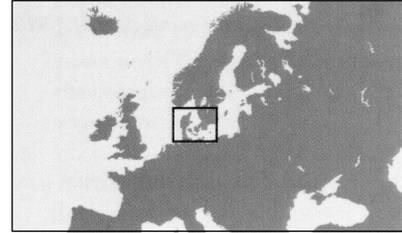
The major civil engineering project currently being undertaken in the northern part of Europe is the construction of a road and rail link to cross Øresund, the narrow sea passage between Denmark and Sweden. This fixed link between Copenhagen and Malmö will be 18 km in length and will consist of a tunnel, an artificial island and a bridge. It will carry a motorway and a double-track railway.

The primary survey control for the project is a high-precision geodetic network which included GPS observations. Real-time GPS reference stations were established and tied to this primary geodetic network. These reference stations transmit RTCM V 2.1 messages for use by all real-time GPS rover units working in the area and log RINEX 2.0 data to bulletin boards for subsequent post-processing requirements. Quality control is provided by integrity monitoring at the reference stations and by the fact that rover units can switch instantly from one reference to another to check position-fixes. The system is designed to provide real-time GPS surveying accuracies of 3 cm or better throughout the entire working area.

This paper describes the concept, development and operation of this network of real-time reference stations designed to support centimetre-accuracy, real-time GPS surveying for civil-engineering, construction, positioning and precise navigation.

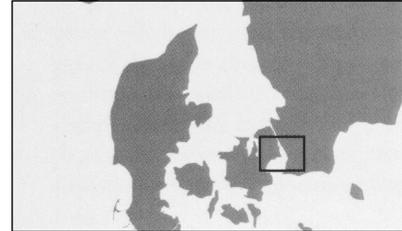
## Introduction

In 1991, the Danish and Swedish governments decided to build a fixed link across Øresund to connect Copenhagen with Malmö. When finished, this new road and rail connection will be a vital link in the European transportation network and will bring important benefits to Denmark and Southern Sweden. The project is currently the largest civil-engineering work being undertaken in Europe and is one of 14 priority projects within the Trans-European network. Completion is planned for the year 2000.



Denmark and Sweden established Øresundskonsortiet to be responsible for the design and implementation of the project.

The Fixed Link, which will carry a motorway and dual-track railway, will leave Denmark in the vicinity of Copenhagen international airport and go ashore a few kilometres south of Malmö in Sweden. The first 3.5 km on leaving Denmark will be an immersed tunnel (trench). After the tunnel, an artificial island south of Saltholm will carry the road and railway for about 4.1 km. Finally there will be a bridge 7.8 km in length between the artificial island and Sweden and crossing the main shipping channel.



Initial construction of dikes and breakwaters started in 1995 with GPS surveying being widely used. One contractor has even developed a system of machine control based on Leica real-time GPS for the excavators building the breakwaters.



**Figure 1: Alignment of the Fixed Link**

Once the work was underway, it soon became obvious that it would be impossible to allocate a separate radio frequency to each of the many contractors and survey companies that would use GPS as a survey tool. Local Telecom authorities agreed to provide separate radio frequencies for up to 6 GPS reference stations.

A carefully established network of fixed GPS reference stations would also be a major advantage for the surveying, setting out and precise navigation tasks that have to be undertaken by the various contractors working on the project. This GPS network would also ensure the uniform levels of accuracy and quality control that are essential for a civil-engineering project of this size and complexity.

At the end of 1995, Øresundskonsortiet issued an international tender based on EU rules for the establishment and operation of a network of real-time GPS reference stations and the provision of radios for rover units working on the project. Some 20 companies applied for pre-qualification. Leica was awarded the contract in March 1996.

## The requirement

The primary requirement of the tender was the establishment and operation of 5 real-time GPS reference stations - 2 in Denmark, 2 in Sweden, 1 on the artificial island - that would transmit RTCM V 2.1 messages for use by real-time rover units of any manufacturer and log RINEX 2.0 data for post processing. The positions of the reference stations had to be determined to within 2 cm and the system had to be such that real-time rovers could operate within the project area to accuracies of 2-3 cm. Integrity monitoring to ensure the correctness of the transmitted data was a specific requirement of the tender.

Further requirements of the tender were the provision of a mobile reference station that could be set operational within 24 hours anywhere within the project area and the supply of radio modems to be issued for all real-time rover units working on the project.

The reference stations have to operate 24 hours per day, 7 days per week, for about 5 years. GPS data for real time and post processing have to be available at all times. Failures and downtime have to be held to a minimum and the system has to be easy to maintain and support.

The climatic conditions in the area are harsh: sea environment, rain, snow, strong winds, large variations in temperature etc.. Transmission of RTCM V 2.1 is complicated by the intense radio activity from 2 major cities, an international airport, a very busy seaway, and the construction site itself.

The network of real-time GPS reference stations is a major part of the primary control for the Øresund Fixed Link. Thus, although the reference stations form only a tiny portion of the costs of this huge civil-engineering project, they are of immense importance. The network of reference stations has to be comprehensive, well designed, with integrity monitoring and full back-up facilities.

Establishment of the reference stations eliminates the need for contractors to set up their own references, simplifies the allocation of radio frequencies, and guarantees uniform accuracy and quality control.

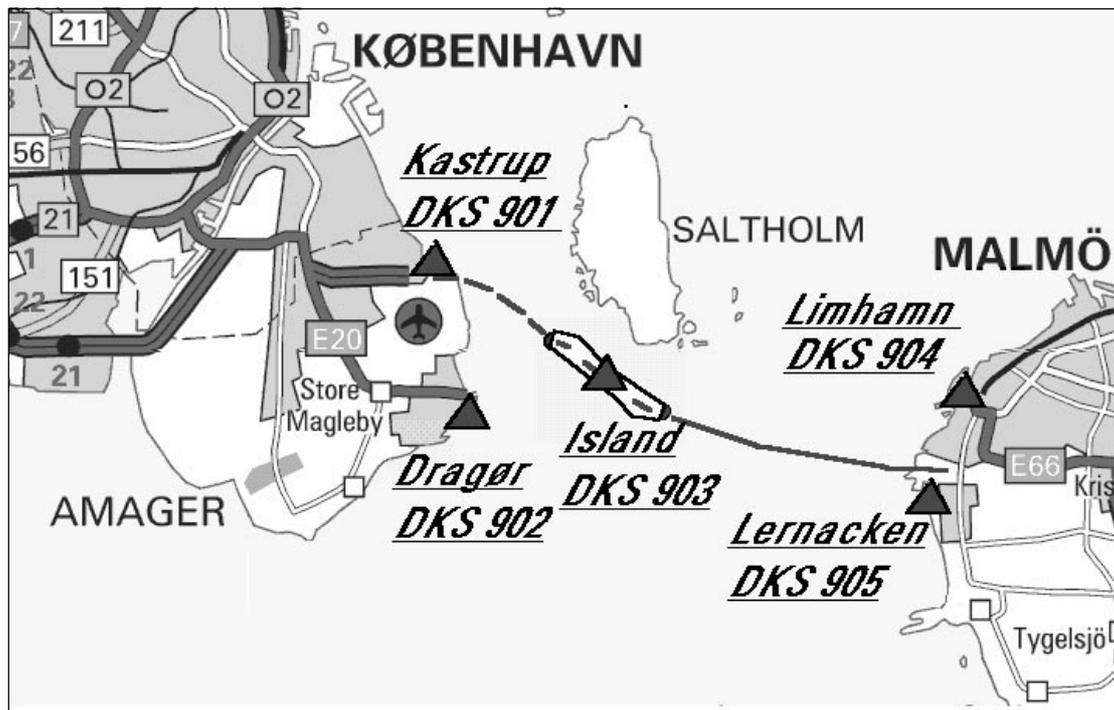
## Multi-purpose, real-time GPS reference stations

The five reference stations were set up as follows (see figure 2):

- DKS901 on top of a disused silo at Kastrup, just north of Copenhagen international airport
- DKS902 on top of a harbour fortification at Dragør, south of the airport
- DKS903 on the artificial island
- DKS904 on top of a cement silo at Limhamn on the outskirts of Malmö
- DKS905 in a lighthouse at Lernacken

The stations cover the project area of approximately 6km x 20km.

Depending on the site, the reference-station equipment is housed in a suitable shelter, radio antennas are on masts, and the GPS antenna is on a pillar. Standard power and telephone services are used at the four mainland stations in Denmark and Sweden. At the island, however, a power generator had to be installed and a mobile phone (GSM) employed.



**Figure 2: Reference station locations in the Øresund project area**

Each station comprises the following three main systems:

1. **Reference system** for transmission of RTCM V 2.1 and logging RINEX 2.0 data
2. **Bulletin-board system** for archiving RINEX 2.0 data files
3. **Integrity-monitoring system** for ensuring the correct functioning of the station and the correctness of the transmitted data (also provides the full back-up system)

The hardware at each station comprises (see figure 3):

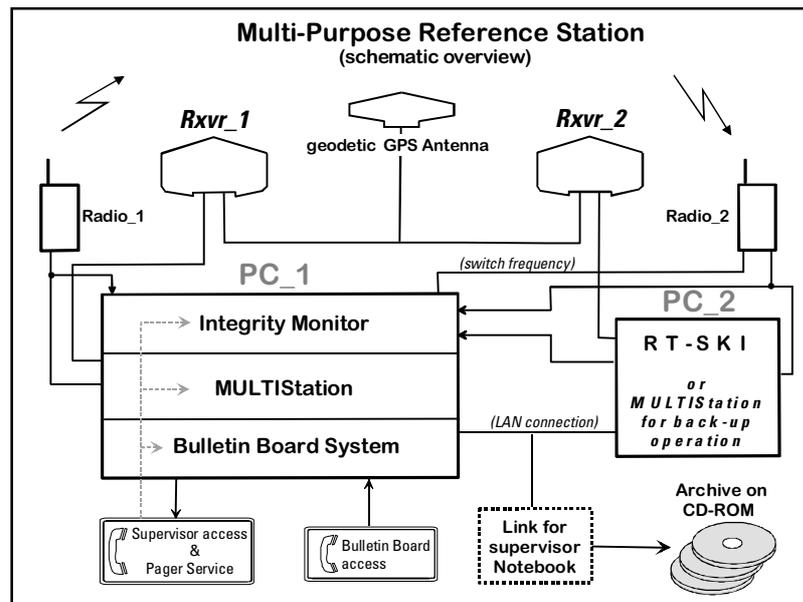
- 2 Leica dual-frequency receivers
- 1 Leica geodetic antenna
- 2 industrial PC's in one housing (the total size is hardly larger than that of a standard PC)
- 2 radio modems
- 2 radio antennas
- 1 uninterruptible power supply
- 2 telephone modems

A separate radio frequency within the UHF band 422-470 MHz is allocated to each station. Transmission is at 10W and 9600 baud. Directional antennas pointed at the project area are used at the four mainland stations. An omni-directional antenna is used at the island station.

The design is such that:

- Each station has a full back-up system in case of malfunction or failure of the primary system
- Authorized users can access the bulletin board and download data files
- The stations transmit status messages to pagers supplied to real-time rover units.
- The system supervisor can log-in remotely to inspect each station

As the reference stations perform a wide range of functions, they have been termed “multi-purpose GPS reference stations”



**Figure 3: Multi-purpose reference station, schematic overview**

The radio modems supplied for use with real-time rover units are equipped with a manual switch for changing frequency. Thus the rover operator can switch frequency from one reference station to another for independent real-time position fixes and immediate, on-the-spot quality control.

## The reference system

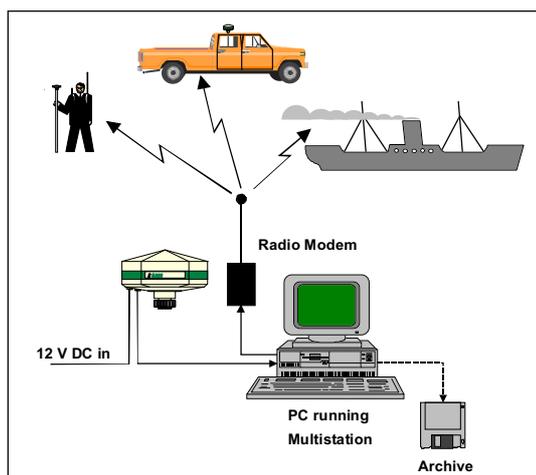
The reference-system part of each multi-purpose GPS reference station performs the two principle tasks: the transmission of RTCM V 2.1 messages and the logging of RINEX 2.0 data.

The reference system comprises (see figure 3):

- A Leica geodetic antenna (GPS antenna)
- A Leica dual-frequency receiver (Rxvr 1)
- A Radio modem with 10W output power (Radio 1)
- A PC with 2 harddisks (PC1)
- Leica Multistation software running on harddisk 1 of PC1

Multistation is a standard software developed and marketed by Leica for all reference-station applications. It controls the receiver, logs hourly RINEX 2.0 data files, and transmits RTCM V 2.1 messages via the radio modem.

Multistation stores the hourly RINEX files on harddisk 1. A data-management tool compresses the files and copies them immediately to the bulletin-board archive on harddisk 2



**Figure 4: Reference station system**

## The bulletin board system

The compressed 1-hour RINEX files are available immediately in the bulletin-board archive on harddisk 2. Authorized users are given passwords and can dial in and download files for post-processing purposes.

Files are kept on both harddisk 1 (Multistation) and harddisk 2 (bulletin-board archive) for at least 4 weeks until copied to CD ROM for permanent archiving. Full data security is ensured.

## The integrity monitoring system

The tender called for integrity monitoring to ensure the correct functioning of the stations and the validity of the transmitted RTCM V 2.1 messages.

The integrity-monitoring system at each station is based on (see figure 3):

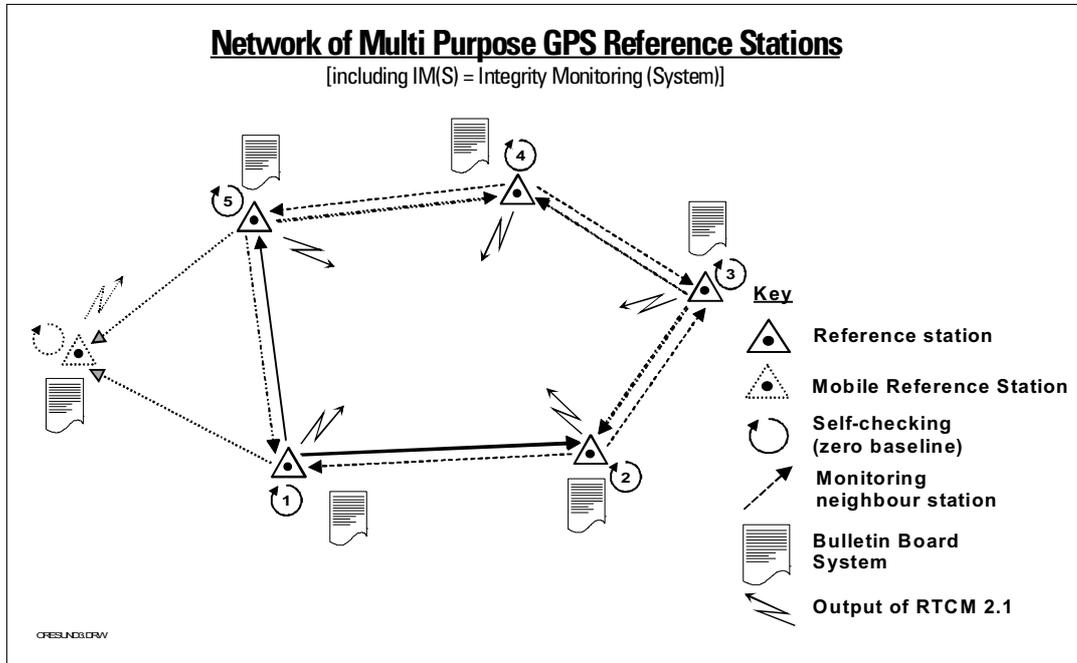
- A second Leica dual-frequency receiver connected to the GPS antenna (Rxvr 2)
- A second radio modem, the frequency of which can be switched (Radio 2)
- A second PC with 1 harddisk (PC2)
- Leica RT-SKI real-time software running on PC2
- Integrity-monitoring software running on PC1

The two receivers, Rxvr1 and Rxvr2, are connected to the same GPS antenna to form a zero baseline. Radio 1 transmits RTCM V 2.1 messages and radio 2 receives them. The RT-SKI real-time software running on PC2 computes continuous on-the-fly ambiguity-resolution fixes for the zero baseline. This computation provides a perfect internal check on the operation of the station and the correctness of the transmitted RTCM V 2.1 data.

By switching the frequency of radio 2 to that of the neighbouring stations, the baselines to these stations can also be computed “on-the-fly in real time” to provide additional monitoring of the reference-station network.

In practice, the integrity-monitoring system at each multi-purpose GPS reference station cycles continuously through the following sequence:

- Zero baseline (self monitoring)



**Figure 5: Reference station network**

- Neighbouring reference 1
- Zero baseline (self monitoring)
- Neighbouring reference 2, or mobile reference
- Zero baseline (self monitoring)
- and so forth

Full information on the operation of the station and the neighbouring stations is obtained.



An automatic paging system warns the system supervisor of any malfunction or if any hardware or software component at a station has to be attended to.

The paging system also provides status messages for the operators of GPS rover units should any station not function perfectly for some reason.

## Full back-up system

The hardware used for integrity monitoring also has an important second function, the provision of a full back-up system in case of any malfunction of the GPS reference station.

If either receiver 1 or radio 1 or PC1 or the software running on PC1 should fail or malfunction, the system switches automatically to receiver 2, radio 2 and PC2 in order to keep the station operational (see figure 3).

Multistation will start automatically on PC2, radio 2 will transmit RTCM V 2.1 messages, and RINEX files will be stored on PC2. The real-time GPS reference station will continue to operate with almost no interruption, transmitting RTCM 2.1 data and logging RINEX files. Users of real-time rover units working on the construction site will experience no down time and can continue operating normally.

The system supervisor will be paged immediately and will log-in to inspect the station. He will either reset it for normal operation from his remote terminal or visit the site for a service inspection.

The provision of a complete back-up system is an important security factor for GPS reference stations that have to function continuously 24 hours a day for about 5 years.

## Mobile reference station

One of the requirements of the tender was the supply of a mobile reference station that could be set up anywhere required by Øresundskonsortiet and put into operation within 24 hours.

The main equipment is housed in a portable, waterproof container, the GPS antenna is tripod mounted, and the radio antenna is fitted on a lightweight mast. The mobile reference operates in exactly the same way as the multi-purpose reference stations transmitting RTCM V 2.1 and logging RINEX data. The only differences are that the level of internal integrity monitoring is reduced and there is no back-up system. Monitoring of the mobile reference is carried out from one or more of the permanent stations.

## System operation and permanent archiving of data

The system supervisor can log-in remotely to all multi-purpose reference stations and to the mobile reference station for inspection and service purposes.

Monthly visits to each station are made for routine service and to download the archived RINEX files to a notebook PC.

The RINEX files are finally archived on duplicate (two) CD ROM's at Leica Denmark. Once this final archiving has been completed, an automatic process deletes the archived RINEX files at the stations. Full data security is guaranteed.

## Survey of the reference station sites

In an initial GPS survey, the real-time reference stations had to be tied into the primary geodetic network for the project. The coordinates of the GPS antennas of the multi-purpose reference stations were determined in both WGS84 and DKS coordinates (local system used for the Øresund-link project). Baseline processing, the least-squares network adjustment for final coordinates, and the computation of transformation parameters between WGS84 and DKS were carried out with SKI software.

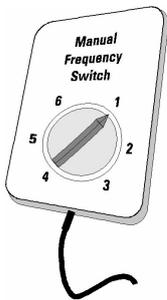
The accuracy of the adjusted coordinates in both WGS84 and DKS is within the 2cm accuracy required by Øresundskonsortiet.

Station descriptions, station coordinates and the transformation parameters between the WGS84 and DKS coordinate systems are available for all contractors working on the project.

As a quality-control check, all baselines between the 5 permanent reference stations are computed at the end of each month using approximately 12 hours of data. The network is adjusted and the results compared with those of the original survey.

## Real-time rovers

Any real-time GPS rover unit of any manufacturer that can receive and process RTCM V 2.1 data can make use of the reference station network. In addition to Leica units, real-time rover units of several other manufacturers are in use or have been tested successfully.



A radio modem with frequency switch is supplied for each real-time rover unit working in the project area. By merely turning the switch, the frequency can be changed instantly from one reference to another. The operator can verify the real-time coordinates at any time by taking fully-independent real-time position fixes from different reference stations. This simple technique provides the field surveyor with a highly-effective system for on-the-spot accuracy checks and quality control.

The project area is roughly 6 km by 20 km with the longest distance between reference stations being about 18 km. The reference stations are sited such that any real-time rover working on the construction site will always be within 10km of three reference stations and at least one of these reference stations will be not more than 5 km away. Distances will often be even shorter.

Short distances to reference stations facilitate rapid ambiguity-resolution-on-the-fly solutions and the 2 to 3 cm accuracy required by Øresundskonsortiet.

With transformation parameters entered, the rover units can work directly in the DKS coordinate system.



## Practical Applications

The network of real-time GPS reference stations was set operational in summer 1996. Several companies working on the Øresund-link project are already equipped with the required radio modems and are using the system for real-time GPS surveying.

As the speed of construction increases over the next few years, it is envisaged that intensive use will be made of the reference-station network by all survey contractors working on the project.

In addition to the uncorrected carrier-phase and pseudorange information needed for real-time GPS surveying, RTCM V 2.1 also contains the differential pseudorange corrections used in standard DGPS applications. Thus, with suitable receivers as rovers, the system can also be used perfectly well for navigation and positioning to sub-metre accuracy levels.

## Conclusion

This is the first time that a network of continuously-operating reference stations with built-in integrity monitoring has had to be established for real-time GPS surveying for a major civil-engineering project.

The reference stations were required urgently as initial construction work had already started. The design of the system, development of special monitoring software, installation of the stations, and putting the entire network of stations into operation had all to be carried out under extreme time pressure. This was a major challenge for all involved.

The system is in full operation and working well for the benefit of all survey contractors operating on the site and will certainly be of primary importance for the construction of the new rail and road connection between Denmark and Sweden.

Leica will operate and maintain the system of reference stations for Øresundskonsortiet until the construction of the Fixed Link across the Øresund sea passage is completed in about the year 2000.

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