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SATELLITE GEODESY AND OFFSHORE OIL

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Updated version of a paper presented at the "Survey and Mapping 1981" Conference and reproduced with kind permission of the organizers, The Royal Institute of Chartered Surveyors.

A review of contributions of satellite geodesy (with other survey techniques) to all stages of oilfield exploration from exploration through engineering to production and unitisation to meet accuracy and repeatability requirements constrained by financial and time cost; possible penalties of an inadequate survey; internal accuracy of the geophysical model; legal and international factors. Rewards and pitfalls of likely future developments are discussed.

This is a slightly updated version of an invited paper given to the United Kingdom "Survey and Mapping 1981" Conference at Reading University. Slides shown during the presentation but not repeated here gave a number of quotations relevant to the topics in hand, but one not included, in spite of the fact that that day (31 March 1981) was the 350th anniversary of the poet's death, was : –

"No man is an island,
Entire of itself;
Every man is a piece of the continent,
A part of the main
If a clod be washed away by the sea
Europe is the less...
....
Never send to know for whom the bell tolls;
It tolls for thee."

(John Donne)

and it seems peculiarly apposite to the questions of North Sea satellite datums (and the consequent positions of the median lines) to now include it in this paper.

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INTRODUCTION

As one who "got his knees brown" early as a Colonial Service Land Surveyor but only recently thrust hydrographic sealegs into brand new welly boots, I was pleased and honoured to be invited to give this review paper. Others are far more experienced in this field (although, as Oscar WILDE said, "Experience is the name everyone gives to their mistakes") but perhaps the organisers (like Dr. Samuel JOHNSON in another context) considered it: "... like a dog's walking on his hind legs; it is not done well, but you are surprised to find it done at all" (Boswell's Life of Johnson, 31 July 1763).

The prime requirement for position-fixing and navigation ("survey" offshore tends to mean seismic survey) is, as on land, to know the user's accuracy requirement.

On coming to military survey in 1959 I became involved with a series of small site surveys which someone had decreed should be to "primary accuracy". An error of one part in 100,000 (or 3 feet in a 60-mile primary triangle side) became 0.12 inches for the typical 1 000 foot line encountered.

I went to Florida the following year to say that we had difficulty in meeting the specification – our masters thought for a moment and said gently would it help to multiply by ten ?

The following section examines some of the accuracy parameters involved at the various stages of oilfield exploration.

SURVEY USERS AND THEIR NEEDS

A) Exploration

The relevant objects of exploration are:

(a) To map overall geological structure and identify possible hydrocarbon traps (exploration surveys);

(b) To identify and assess drilling hazards such as seabed obstructions and shallow gas pockets (site surveys);

(c) To navigate drilling rigs and drillships into position;

(d) To prove the existence of the hydrocarbons and evaluate their production potential in terms of quantity, quality and cost of recovery (exploration drilling);

(e) To fix wellhead positions sufficiently accurately:

 i) to navigate a rig back on station if it is forced off during drilling or if a hole is plugged and suspended to be later reoccupied;

 ii) to relate wellsite geology and oilflow data to the overall geological model of the field.

With the possible exception of areas where magnetics and gravity have some relevance, all subseafloor geophysical investigation in U.K. offshore waters is by seismic reflection :

(a) *deep seismic* for the regional and site surveys – low frequency acoustic "bangs" near sealevel reflected from each interface between subsurface geological strata and sensed on hydrophones spaced at equal intervals along a seismic streamer which is towed across the area at the same depth as the source;

(b) *shallow seismic* for the shallow obstructions – higher frequency acoustic signals, generated by sparker, boomer, etc., but similarly sensed on single hydrophones or short arrays.

The resulting geological model has a vertical resolution of 0.1 wave lengths of the acoustic signal and an expected accuracy of anything between this and 0.5 wave lengths (assuming horizontal reflectors at this stage).

When the reflecting interface is not horizontal the point of reflection is displaced upslope from the common depth point (CDP) of the seismic stack.

This is compensated ("migration") for the component of slope along the seismic section but the residual error ("sideswipe") resulting from the other component of slope across the line remains much less well known and can be significant unless : –

(a) the spacing of the seismic grid is very close;

(b) the slope varies very smoothly across the area.

Experience suggests that the main cause of residual error in the model is lack of knowledge of the variation of seismic velocity with depth and that unless unusual structure causes significant lateral variations of this vector the plan error in the resulting model will be somewhat less than the vertical error.

Typical examples of vertical accuracy are :

(a) *deep seismic :* frequency 20-40 Hz
average velocity 3 500 metres/second
hence wave-length 90 to 175 metres
for a typical model at depth 4 kilometres derived from a 3 kilometre streamer :
Vertical accuracy 9 to 88 metres.

(b) *deep seismic :* frequency 40-60 Hz
(shallow end) average velocity 2 000 metres/second
hence wave-length 35 to 50 metres
for a typical model at depth 1 kilometre with streamer as before :
Vertical accuracy 3 to 25 metres.

(c) *shallow seismic :* frequency 80-100 Hz
(sparker) average velocity 2 000 metres/second
hence wave-length 20-25 metres
for a typical model at depth 0.5 kilometre derived from a 1 kilometre streamer :
Vertical accuracy 2 to 15 metres.

When vertical wells are drilled (deviating in practice by as much as 8° from the vertical) the downhole distance in feet is known to 0.2 times well depth in thousands of feet (WOLFF and WARDT) – although since well direction changes very slowly such error has at most a second-order effect on the positioning of the hole itself as distinct from the "survey points" along it. Direction (which is much more critical) is normally observed by :

(a) *gyro-compass* in the upper sections giving angles of inclination and azimuth to some 0.75 feet per thousand feet of hole (or 2 1/2 minutes of arc for the vector offset – mostly inclination) – this gives accuracy relative to the surface azimuth used to set up the gyro and takes no account of the additional systematic error imposed by a surface positioning error in this initial direction;

(b) *magnetic compass* in the lower sections giving the same data to some 2 feet per thousand feet of hole (or 6 1/2 minutes of arc for the vector offset);

(c) *inertial systems,* not at present much used for vertical holes, but likely to have a basic repeatability of better than 0.5 feet per thousand feet of hole and (since they sense the earth's rotation as the compass senses the earth's magnetic field) not subject, as is the gyro compass, to systematic directional error from the surface positioning.

If the errors in each 1 000 foot section are *random* (this is considered again later for the case of deviated wells) then g sections of 1 000 feet with gyro followed by m sections with magnetics and an average observed inclination i to the vertical for the whole well will give :

Vertical accuracy $\frac{3\sqrt{g} + 8\sqrt{m}}{4} \sin i + 0.2\sqrt{g+m} \cos i$ feet

Plan accuracy $\frac{3\sqrt{g} + 8\sqrt{m}}{4} \cos i + 0.2\sqrt{g+m} \sin i$ feet

(relative to surface position)

with the hole itself (see above) accurate to $\frac{3\sqrt{g} + 8\sqrt{m}}{4}$ feet, but if they are *systematic* one has :

Vertical accuracy $\frac{3g + 8m}{4} \sin i + 0.2\ (g + m) \cos i$ feet

Plan accuracy $\frac{3g + 8m}{4} \cos i + 0.2\ (g + m) \sin i$ feet

(relative to surface position)

with the hole itself (see above) accurate to $\frac{3g + 8m}{4}$ feet.

For a typical well with 6 000 feet of gyro followed by 4 000 feet of magnetics and an 8° inclination to the vertical this becomes :

Vertical accuracy	1.6 feet
Plan accuracy	5.9 feet
Hole lateral displacement	5.8 feet

for random errors, but,

Vertical accuracy	4.5 feet
Plan accuracy	12.8 feet
Hole lateral displacement	12.5 feet

for systematic errors.

B) Appraisal and development planning

The relevant objects of appraisal and development planning are :–

(a) To refine the reservoir model (and agree it with adjacent operators for unitisation if it overlaps block boundaries or international median lines) by :
  i) seismic infill (development survey);
  ii) confirming its extent and estimating its volume (stand-off drilling and evaluation drilling);
  iii) formation evaluation for estimating porosity, saturation, permeability and recoverability (coring, well-logging, pressure and flow recording).

(b) To plan efficient exploitation in terms of :
  i) primary drive mechanism (gas, water or combination drive);
  ii) production well geometry (to maintain primary drive and minimize unwanted migration);
  iii) secondary recovery (injection wells and acidisation);
  iv) depletion planning (extraction rate for maximum economic recovery).

(c) To plan efficient transportation by :
  i) offshore loading on tankers (survey for navigation hazards);
  ii) pipelines (regional bathymetry and pipeline route surveys).

Seismic infill during appraisal will often be by three-dimensional survey with greater accuracy than during exploration – perhaps by a factor of 2.

Well accuracies are as during exploration since deviated drilling will normally be at production phase.

In a field divided between several operators and requiring unitisation, the equity allocated to each operator (computed from an estimation of the "available oil in place" in each block) is normally quoted (as a fraction of unity) to at least 6 significant figures.

As a very crude model, take such a field to be a rectangular slab 4 miles square with a vertical thickness of 300 feet, and with an assigned value of £700,000,000 so that the last unit of the equity figure corresponds to £700.

While porosity, saturation, permeability and recoverability are all (with the reservoir volume) factors in the equity formula, and while several of these are at best only known to three significant figures (so that their product, the equity, is seen to be something of a legal fiction but a definite financial reality), it is worthy of note that a shift of one metre of the field in relation to the legally defined block boundaries between the operators will vary the last three units of the equity by 155, or £109,000 in the example.

Hence the equity determination to the accuracy of six significant figures is sensitive to a *centimetre change* in absolute position (i.e. in relation to European Datum as defined on the mainland).

Pipeline surveys ensure that the seabed route chosen has suitable shallow structure free of obstructions with gentle slopes (shallow seismic with bathymetry) and while the route should be as direct as possible, its radius of curvature should not be less than, say, 2 kilometres for a typical 24-inch pipe.

When connecting the pipeline to the riser great accuracy, to centimetres, is required to ensure a stress-free connection.

C) Production

The relevant objects of production are :

(a) to confirm the reservoir model and update the exploration plan by continuous flow and pressure monitoring, for maximum economic recovery;
(b) to transport the product onshore.

Production platforms are installed requiring site surveys and navigation similar to those of other wellsites but with greater accuracy consonant with the extended structures, the improved knowledge of the reservoir model and the need to avoid subsurface collision by wells deviated (see later) from adjacent platforms.

Deviated wells, up to as much as 65° from the vertical are drilled from a platform in order to increase its extraction area. Both gyro and magnetic compass surveys are then significantly worse than suggested on page 34 since :

(a) *gyro-compass,* being balanced so that the rotor precesses horizontally (and, for some systems, with physical limitations on the gimbal construction), becomes increasingly unstable at higher inclinations – WOLFF and WARDT suggest a multiplying factor of sec i, where i as before is the inclination of the hole;
(b) *magnetic compass* is subject to interference from remanent magnetisation of the drill string (magnetic hysteresis) and indeed from the very small penlight torch used to illuminate the compass card. This axial disturbing field will have no horizontal component when the hole is vertical and so will not deflect the compass, but if one assumes (with WOLFF and WARDT) an axial downhole field of 1.1 micro-Teslas, this will have :

a) a horizontal component of 1.1 sin i micro-Teslas

and b) an east-west horizontal component of 1.1 sin i sin A micro-Teslas where i is the inclination as before and A is the azimuth of the hole

so that if the horizontal component of the earth's field in the North Sea is taken as 16 micro-Teslas (it is of the order of 11.3 at Tromso in Northern Norway, 14.7 at Lerwick and 19.0 at Greenwich with annual variations of 0.016, 0.020 and 0.014 respectively) one has a compass deflection of :

$$\tan^{-1}((1.1/16) \sin i \sin A) \text{ or } \underline{3°56' \sin i \sin A}$$

To this remanent magnetic interference effect must be added any systematic error in the compass itself and in the international geomagnetic reference field (WOLFF and WARDT are perhaps a little pessimistic to suggest 1.5°) before multiplying by sin i to give the lateral horizontal displacement of the hole.

For this reason, it is common practice with deviated wells to use an inertial system down to the end of the 13 3/8 inch casing followed by gyro-compass in the middle sections (with a 1 600 foot overlap on the inertial work for comparison, calibration and drift control); it is then normal to ignore the wire-line downhole distance (with a nominal accuracy of 200 parts per million, see page 34) for the inertial section and to use instead the separate x, y and z increments in distance got from the inertial (with an expected basic repeatability, ibid, of $500/\sqrt{n}$ parts per million for random error in n sections of 1 000 feet but 500 parts per million if the errors are systematic – hence the assumption is made that the inertial errors are indeed random).

Unless the azimuth of the hole is within 45° of an east-west direction, when the compass error terms in sin A become inconveniently large, the bottom sections of the hole may well be surveyed by magnetic compass – on the grounds that gyro takes 24 to 36 hours of expensive drilling time per survey (compared with negligible extra time for a magnetic survey) rather than from a comparison of the specific costs of the two systems (see later, "Financial and time cost considerations", last-but-one paragraph, for surface surveying systems, where similar considerations apply).

Hence for deviated wells (n sections of 1,000 feet with inertial survey, followed by g sections with gyro or m sections with magnetics – the analysis allows all three but this would be most unusual in the same hole) the formulae of page 34 become :

a) *Random error* (plus systematic in the magnetics)

Vertical accuracy

$(\sqrt{n}/2 + 2\sqrt{m})\ \sin i + 3/4\sqrt{g}\ \tan i + (26 + 69\ \sin i\ \sin A)\ m\ \sin^2 i$
$+ 0.2\sqrt{g + m}\ \cos i$ feet

Plan accuracy

$(\sqrt{n}/2 + 2\sqrt{m})\ \cos i + 3/4\sqrt{g} + (26 + 69\ \sin i\ \sin A)\ m\ \sin i\ \cos i$
$+ 0.2\sqrt{g + m}\ \sin i$ feet

Hole lateral displacement

$(\sqrt{n}/2 + 2\sqrt{m}) + 3/4\sqrt{g}\ \sec i + (26 + 69\ \sin i\ \sin A)\ m\ \sin i$ feet

where i is inclination as before

A is azimuth of the hole

26 and 69 represent sin 1°30' and sin 3°56'.

b) *Systematic error* (but inertial errors assumed random)

Vertical accuracy

$(\sqrt{n}/2 + 2m)\ \sin i + 3g/4\ \tan i + (26 + 69\ \sin i\ \sin A)\ m\ \sin^2 i$
$+ 0.2\ (g + m)\ \cos i$ feet

Plan accuracy

$(\sqrt{n}/2 + 2\ m)\ \cos i + 3g/4 + (26 + 69\ \sin i\ \sin A)\ m\ \sin i\ \cos i$
$+ 0.2\ (g + m)\ \sin i$ feet

Hole lateral displacement

$(\sqrt{n}/2 + 2m) + 3g/4\ \sec i + (26 + 69\ \sin i\ \sin A)\ m\ \sin i$ feet.

Hence for a typical deviated well with 5,000 feet of inertial at an average 30° inclination, followed by 5,000 feet of gyro at an average 55° inclination, one has for all azimuths of hole :

Vertical accuracy	3.2	feet
Plan accuracy	3.0	feet
Hole lateral displacement	4.0	feet

for random errors, but

Vertical accuracy	6.5	feet
Plan accuracy	5.5	feet
Hole lateral displacement	7.7	feet

for systematic errors. However, if the gyro is then replaced by 5,000 feet of magnetics at the same inclination, the formulae give, for various azimuths of hole :

	Azimuth			
	0°	45°	90°	
Vertical accuracy	91.7	225.8	280.8	feet
Plan accuracy	65.0	158.9	197.8	feet
Hole lateral displacement	112.1	275.8	343.6	feet

for random errors, but

Vertical accuracy	97.1	230.6	286.2	feet
Plan accuracy	68.6	162.5	201.4	feet
Hole lateral displacement	117.6	281.3	349.1	feet

for systematic errors. It may well, and with reason, be felt that these figures do the magnetic system less than justice for deviated holes running substantially north-south – in which case the "culprits" are the terms with coefficient 26 corresponding to an assumed systematic magnetic error of 1.5° (see comment in last para on this subject).

The downhole positioning techniques are as described earlier for the vertical wells but if the platform is of steel construction, consideration must be given to the distance up to which induced magnetism in the structure will cause systematic error in a down-hole magnetic compass (see page 34).

If, as an approximation, one treats the platform as a uniform cylinder of height H, radius a and magnetic susceptibility k in a field with horizontal component X and vertical component Z, and if one refers a general point (x, y, z) to a right-handed system of local coordinates, origin the centre of the base of the cylinder with x in the direction of X and Z vertically *upwards* (opposite to Z), then, to a first order :

Compass deflection $= 3M/r^5\, y\, (x - z \tan I)$ radians

where $r^2 = x^2 + y^2 + z^2$ (the slope distance)

$M = k\, (\pi a^2 H)$ (the "platform magnetic model")

I is the dip-angle ($\tan^{-1} Z/X$)

and the cylinder dimensions are small compared with r, while using :

$$FdF = XdX + ZdZ \quad (Y = 0)$$

for the variation dF in total field F one has :

$$dF = 3MF/r^5\, (x \cos I - z \sin I)^2 - MF/r^3.$$

POSITIONING TECHNIQUES AVAILABLE

General considerations

(a) Ratio to line of sight
(b) Fixed or moving
(c) Extent of area
(d) Day or night
(e) Permanent marks
(f) Accuracy

are criteria on which the choice of system may be based.

If the area is less than line of sight from reliable fixed control then :

(a) Simple fixed positions should be obtained by conventional terrestrial systems measuring range and/or direction directly :
 i) *optical systems* such as theodolite or laser ranger;
 ii) *short range EDM systems* such as Trisponder or Mini-Ranger (measuring range) or Artemis (measuring range and bearing) – or Syledis (measuring ranges up to 3 × line of sight).

(b) Positions of a moving vessel (such as one making a seismic survey) require similar equipment but supplied with a real-time plotter and automatic data logger (unless so little data is required that it can be hand-logged).

There will rarely be occasion to use satellite doppler in the less than line of sight region – unless the fixed control points to be used for the survey have not got coordinates on the correct datum or their coordinates are suspect in some way, in which case it is quite proper to observe doppler at the fixed control points to adjust the local terrestrial survey network.

If there are no permanent structures in or around the survey area and if it is intended to return there for further connected surveys later then there is merit in putting down a seabed acoustic transponder array since :

(a) they can be used (with doppler calibration on this occasion) to help control the shape of the current survey, if the area of survey is not too extensive;
(b) they can act (for the life of their batteries) as permanent seabed marks to which the next survey can be tied.

It may be noted that the line of sight distance is very much a function of the height above sea level at the far station. Taking the vessel height as 50 feet and using the *optical* curvature plus refraction rule-of-thumb (quite adequate for the present purpose) :

$$0.57\ (\text{distance in miles})^2 = \text{height in feet}$$

one has for various far station heights the following "L.O.S." values :

h feet	L.O.S. miles	L.O.S. km
0	9.37	15
50	18.74	30
100	22.62	36
200	28.10	45
500	38.99	63
1,000	51.26	82
2,000	68.60	110
SNOWDON	88.40	142
BEN NEVIS	97.29	157

and one needs to have due regard for sea-coast topography when planning line of sight surveys or when looking (see later) for range-holes.

If the area is beyond line of sight of land and of fixed offshore structures then :

(a) Single fixed positions may be obtained by :
- i) *Syledis* as before (up to 3 × line of sight);
- ii) *Offshore hyperbolic systems* such as Pulse 8 or Hi-Fix 6;
- iii) *Satellite doppler* (three dimensional solution deriving height above spheroid and so geoid-spheroid separation as a by-product).

(b) Positions of a moving vessel (such as one making a seismic survey) may be obtained by :
- i) *Similar equipment* (with the exception of satellite doppler) but supplied with a real-time plotter and automatic data logger;
- ii) *Satellite doppler* but additionally supplied with its necessary velocity input which may be from :
  - (a) Doppler sonar;
  - (b) Loran C with caesium/rubidium clock;
  - (c) Acoustic transponder network such as Oasis;
  - (d) Some other positioning source in an integrated system with the doppler.
- iii) *Offshore range-range systems* such as Pulse 8 (Rho-3 mode) or Argo.
- iv) *Integrated systems* consisting of two or more of the above.

When using Syledis there is some evidence for a "range-hole" around the 1.8 to 2.2 times line of sight range, when reflected signal cancels out the direct signal and no measurement can be made.

Evidence for this is conflicting, although a paper by GILB and WEEDON, of Motorola, suggests that something similar can be encountered with other radio systems (they discuss specifically the Mini-Ranger) and use of the electromagnetic equivalent of the combined curvature and refraction table given above would make it comparatively simple to avoid shore stations for which this condition applied.

When using *Pulse 8* and similar hyperbolic systems it is highly desirable to have a reliable value of the 'C − O' calibration correction which must be applied to the hyperbolic lane readings to give the true position, and if these are not available it is worth making every effort to establish them oneself, as well as checking out the receiver against a known position while on passage to the survey area.

Anomalous results have been encountered from time to time and it is no safeguard to rely on having three independent patterns which give a triangle of error within Decca's rather generous quoted accuracy figure of 50 metres.

As an experiment at a time when there was some evidence that systematic errors of 0.15 microseconds might occur in one or more patterns of Pulse 8, a genuine set of readings of 3 independent patterns in quadrant 15 were examined, for which the "cocked hat" had shown a quite acceptable standard error of 16 metres.

All possible combinations of plus and minus 0.15 microseconds were then added to the readings and the result was no less than 7 different triangles of error smaller than the original of which the three smallest represented standard errors of 2, 2 and 5 metres respectively.

This is particularly likely in an area for which the four transmitters are symmetrically disposed about the survey receiver where a displacement to one side which increases two pattern readings by one unit will, by symmetry, decrease the other two by the same one unit.

Pulse 8 in range-range mode is likely to be used in preference to hyperbolic in areas remote from the transmitters where another effect, which may be called range-range distortion, can be encountered.

If the survey area is inside the triangle formed by the transmitters (where in practice one would probably use hyperbolic mode) the range-range triangle of error would be such that an equal addition (or subtraction) applied to all three ranges would close it down to the centre of the inscribed circle.

This is exactly the hyperbolic fix from the same observations – and those contractors who solve a range-range triangle by taking the centre of the inscribed circle are simply converting the range-range observations back to hyperbolic.

If the triangle of error becomes consistently too large, the range-range system automatically adjusts its time standard to bring it back down – so that a hyperbolic fix is simply the limit of this procedure when the triangle is closed to zero at every point.

If, on the other hand, one is outside the triangle formed by the transmitters, then the hyperbolic fix corresponds to the centre of the *escribed* circle opposite the "middle" of the three distant transmitters – and this circle will in general be much bigger than the inscribed circle for the same triangle.

For a triangle of error ABC, with A opposite the middle transmitter and $R = a/2 \sin A$ = etc., the radius of the circumcircle, one has:

Radius of inscribed circle $= 4R \sin A/2 \sin B/2 \sin C/2$

Radius of relevant escribed circle $= 4R \sin A/2 \cos B/2 \cos C/2$

while the centres are separated by $4R \sin A/2$ or a bearing which is the mean of those to the two "outside" transmitters.

The ratio ($\cot B/2 \cot C/2$) of escribed to inscribed radius is always greater than 1 (it is 3 for an equilateral triangle of error) and if the range-range system has wrongly identified random error in the ranges as timing error the corresponding shift of 4R sin A/2 (the "range-range distortion") will have been introduced.

One can loosely consider the factor cot B/2 cot C/2 as the price one pays for greater range-range local consistency compared with greater hyperbolic random error and one must judge the "mix" of systematic to random error in any given situation when choosing between the two.

It follows that:

(a) Range-range Pulse 8 should preferably not be used without prior knowledge of range-range 'C – O' values;

(b) If not, then the best available estimate should be used – possibly (see later) one using a formula such as the LORAN-C – rather than the common practice of using zero 'C – O' throughout;

(c) If only hyperbolic 'C – O' values are available, the practice of using these for range-range with zero at the master can also introduce range-range distortion;

(d) If, subsequently, better 'C – O' values (either range-range or hyperbolic) become available, these should not be used for a postplot computation without 'doctoring' them to remove the distortion which the real-time range-range system has already introduced.

An important element in all microwave systems is the transmission velocity adopted and, although systems operating beyond line of sight are predominantly affected by phase-lag (and possibly sky-wave interference) which are functions of:

(a) aerial design and surface conditions near transmitter and receiver;

(b) path-length and height above the surface;

(c) permittivity and conductivity at the surface (sea-path and land-path);

(d) meteorological conditions (time of day);

it may be instructive to consider the basic transmission velocity operating over and above these factors.

Refraction may be expressed in a modified form of ESSEN and FROOME's formula as:

$$\frac{0.2842\ P}{1 + t/273.15} + hE^{*} \text{ parts per million}$$

where P is total pressure in millibars
t is temperature in °C
h is relative humidity (as a fraction of unity)

$$E^{*} = 4.9372\ \frac{1 - t/28505.55}{1 + t/273.15}\ e'$$

and E^{*} is tabulated below using KAYE and LABY's values for the water saturation pressure e' from 0 to 48 °C:

t °C	0	10	20	30	40
0	30.15	56.38	100.17	169.98	276.88
1	32.18	59.85	105.81	178.79	
2	34.32	63.50	111.73	187.99	303.88
3	36.59	67.33	117.92	197.59	
4	38.98	71.37	124.41	207.58	333.03
5	41.51	75.61	131.19	218.00	
6	44.18	80.05	138.28	228.85	364.46
7	46.99	84.73	145.70	240.15	
8	49.96	89.63	153.44	251.91	398.32
9	53.09	94.77	161.53	264.15	

Taking as typical the ICAO standard atmosphere which is "representative of average atmospheric conditions in temperate latitudes" one has :

Altitude (metres)	Pressure (millibars)	Temperature (°C)	Refraction (parts per million)	
			h = 0	h = 100 %
0	1013 (0.25)	15	272.98	348.59
250	984	13	266.95	334.28
500	955	12	259.99	323.49
750	926	10	253.87	310.25
1000	899	8	248.23	298.19
1500	846	5	236.11	277.62

If one takes 85 % as an average figure for relative humidity in home waters, the adopted SYLEDIS transmission velocity of 299 695.0571 kilometres/second (or 325 parts per million refraction) corresponds to an ICAO altitude of 235 metres above sea-level, while the adopted MINI-RANGER transmission velocity of 299 696.524 kilometres/second (or 320 parts per million refraction) corresponds to 349 metres ICAO altitudes.

However, perfectly possible changes of 20 °C temperature or 50 millibars pressure to the ICAO model would change the computed refraction by 94 and 14 parts per million respectively – or 11.3 and 1.7 metres in a distance of 120 kilometres (compared with a quoted SYLEDIS accuracy of ± 1 metre) and greater variations could be expected in other parts of the world.

The PULSE 8 transmission velocity takes account of phase-lag and one has either :

(a) A *fixed velocity* of 299 594 kilometres/second (or 662 parts per million refraction)

or

(b) A *velocity varying with range* (expressed as a mean velocity over distance) from a U.S. COAST GUARD LORAN-C formula which may be written as :

$$\bar{v} = \frac{299\,498.695}{1 - 0.124166/d + 12.03185/d^2}$$

where d ($\geqslant$ 160) is the distance in kilometres

$\bar{v}$ is the average velocity in kilometres/second.

This last is equivalent to an instantaneous velocity v at distance d :

$$v = \frac{299\,498.695}{1 - 12.03185/d^2}$$

and the equivalent parts per million refractions for different distances are :

Distance (km)	$\bar{v}$	v
160	674.51	510.39
200	660.50	679.76
300	700.38	847.03
400	745.40	905.58
500	780.45	932.67
555	796.01	941.75

If one looks on these formulae as in some measure representing a "base velocity", e.g. 299 690 times a "geometrical" phase-delay factor in d, then it intuitively seems likely that temperature and pressure variations would vary the base velocity as before – and hence the phase-lagged parts per million in proportion.

Thus (see page 43) typical changes of 20 °C temperature or 50 millibars pressure to the ICAO model would change the PULSE 8 refraction by :

(a) 197 and 29 parts per million respectively
(or 32 and 5 metres) at a range of *160 kilometres*

(b) 232 and 35 parts per million respectively
(or 129 and 19 metres) at a range of *555 kilometres*

(compared with a quoted PULSE 8 accuracy of 50 to 100 metres at up to 555 kilometres) – and greater variations in temperature and pressure could be expected in other parts of the world.

Satellite geodesy

Satellite doppler has the great advantage that it is a worldwide system with massive technical support, both civilian and military, and has been long enough in operation (18 years) to be reasonably trouble-free, while it is expected to remain in its present form for at least another 9 years (1990).

Moreover, it is a system that the positioning contractor cannot "stick his fingers into" to alter : he has to supply a reliable velocity if the receiver is not on a fixed platform (one knot of northings error can give a longitude error of anything from 400 to 850 metres) and a reasonable geoidal separation (10 metres error in geoid can give a longitude error of anything up to 30 metres – this will be eliminated if the passes are properly balanced, for doppler on a fixed platform) and he can do what he will with the output, but the central process (often using software only accessible to the receiver manufacturer) gives the only result it can.

The obverse of this advantage is that, if the manufacturer's software is in any way inadequate, little can be done – except change to a new system.

Errors dv_E, dv_N knots in the velocity components arise from errors dv_1 dv_2 knots in the velocities along and across the ship's heading A and dA degrees in the heading itself as :

$$dv_E = r \sin (A - a)$$
$$dv_N = r \cos (A - a)$$

$$\text{where } a = \tan^{-1} \frac{dv_2 - v_1 \, dA \, \pi/180}{dv_1 + v_2 \, dA \, \pi/180}$$

$$r^2 = (dv_2 - v_1 \, dA \, \pi/180)^2 + (dv_1 + v_2 \, dA \, \pi/180)^2$$

and will generate errors of the order :

$$dE = 400 \, dv_N \text{ metres}$$
$$dN = 120 \, dv_E \text{ metres}$$

in the satellite fix (for the middle range of angles of elevation at closest approach).

Hence :

(a) Positional error will be maximum and east-west ($dE = 400$ r metres, $dN = 0$) when $A = a$

(b) Positional error will be minimum and north-south ($dE = 0$, $dN = 120$ r metres) when $A = a + 90°$

but in general it will not be possible to predict which directions of the heading A these will be. However if (see later) dv_1 and v_1 dA $\pi/180$ are small compared with dv_2 then the heading will be east-west for the maximum positional error and north-south for the minimum positional error.

For a properly adjusted precision seismic gyrocompass, dA will be as small as ± 0.2° but for an ordinary ship's gyrocompass it may be as much as ± 1°.

If SONAR DOPPLER is used for the velocity :

(a) Waterdepth should ideally be between 50 and 500 feet with a hard reflecting bottom – results of deteriorating quality can be obtained down to 700 feet or even 1000 feet but with increasing probability of loss of bottom lock (and of signal)

(b) Sea-state should be better than 6 or again one will lose bottom lock

(c) Pitch and roll should be compensated by inclinometer and one then has what is called a "radial error growth rate" of 100 to 200 metres per hour for a 6-knot ship-speed.

This implies that after travelling 11 650 metres, the accumulated vector position error will be 100 to 200 metres, giving a velocity error of 0.05 to 0.10 knots – but this is an average error over the whole hour and not just the period of the doppler pass.

A plausible solution would seem to be to consider a typical set of doppler counts as occupying 12 minutes and, assuming that the errors in 5 such periods vary randomly over the hour, to assign a position error of $20\sqrt{5}$ to $40\sqrt{5}$ metres to each, giving a velocity error of 0.12 to 0.23 knots to be applied to the satellite doppler pass.

After the pitch and roll compensation has been applied to the doppler sonar one notes that :

(a) The period of pitch and roll for a typical seismic vessel of 250 feet overall is of the order of 6 to 8 seconds and since the roll is some 4 times greater than the pitch, residual errors will make the cross-course velocity error dv_2 some two or three times the along-course error dv_1 (see page 45) and so one should steam north-south for minimum positional error in the doppler fix.

(b) Although the doppler satellite antenna (the point of measurement) has an equal and opposite motion to that of the sonar doppler transducers under pitch and roll, but magnified by the greater distance of the former from the axes of roll of the vessel, the pitch and roll information is not applied to the satellite antenna as the period of the doppler count (23 seconds) represents 2.9 to 3.8 cycles of the disturbance. This suggests :

i) It might be interesting to feed the data in to the antenna velocity and position, to see what effect this had on the final doppler fix.

ii) Failing this (and short of changing the size of the vessel) one could perhaps change to 3 or 6 message-line doppler counts (13.8 or 27.6 seconds) since their periods are better centred on complete cycles of the disturbance (1.7 to 2.3 or 3.4 to 4.6 cycles).

Integration of the satellite doppler with radio-navigation systems to derive the ship's velocity (such as LORAN-C with caesium/rubidium clock and other range-range, or hyperbolic, systems – such as PULSE 8 in either mode) is not so affected by pitch and roll since if the two aerials are mounted side by side they will swing together with the ship.

In addition the velocity error components v_N, v_E (page 45) will be subject to the influence (*independent* of the heading of the ship) of the relative geometry of the receiver and shore-station positions.

However, one feels intuitively that the non-geometric input to velocity error will still be mostly cross-course (velocity observations will not be exactly simultaneous with the doppler counts) and unless the station geometry is unusually directional the north-south steaming rule still holds.

Finally (if the size of survey area permits) perhaps the most satisfying way to supply the velocity is by acoustic transponders, such as Decca's Oasis which has the following features :

(a) The relative geometry of a net of 5 transponders (with a range of about 5 kilometres) is fixed on an arbitrary grid by steaming round and measuring acoustic ranges – this takes 2 to 3 hours for 140 ranges and the least squares result is usually better than a metre vector, although the vertical coordinates are sometimes worse.

(b) The system orients the net (with shape and size now invariable) by gyroscopic compass (to 1°, say) and starts to collect satellite fixes (taking the vessel velocity from acoustic ranges within this local coordinate system) – which it uses to successively shift and swing the rigid net to approach true survey datum.

(c) When 6 satellite fixes have been accepted (this takes 5 to 6 hours, see later) the net coordinate system will be within perhaps 100 metres position and 30 minutes orientation of truth. At this stage, one can "freeze" the system for navigation and continue with other work while continuing to collect satellite passes.

(d) After 30 passes have been achieved the least-squares (if the passes were all balanced) will usually be good to 10 metres in absolute accuracy and the work already done can be postplotted, its size and shape unaltered, on true datum.

True Oasis accuracy depends on good acoustic velocity, normally got by a temperature/salinity dip and assumed constant all the way down.

The vertical coordinates mentioned earlier are compared with echosounder depths – normally more reliable (a systematic discrepancy suggests a wrong acoustic velocity).

This will also propagate horizontal scale error, which is often rather better behaved – consider a scale error (1 + k) applied to slant ranges from two transponders whose true vertical section coordinates referred to an origin (0,0) on the surface above their midpoint are (– a, – h), (a, – h) and take observations at a general point (x, 0) at sea level which is in the same vertical section.

The erroneous fix (x + dx, dh) derived from the observation is given by : –

$$dx = 2kx_2$$
$$dh = k\frac{h^2 + a^2 - x^2}{h}$$

so that the observations give a constant horizontal scale error (1 + 2k) radial from the midpoint but the vertical scale is (1 + k) over the transponders and rises to

$$1 + k\frac{a^2 + h^2}{h^2}$$

over the midpoint while it becomes negative when x is more than $\sqrt{h^2 + a^2}$ (or the slant-range from a transponder to the origin).

Since normal transponders have a depth limit of 1,000 metres, a typical ratio could easily be :

a = 2.5 kilometres, h = 500 metres

giving a massive 26 times vertical scale error at the midpoint compared with that over the transponders.

This seems a logical explanation of an effect which puzzled us at the time, when an Oasis pattern with transponders at the corners of a square with a fifth in the middle seemed to "curl up" at the edges when compared with echo-sounder – obviously the two diagonals were overpowering the centre-point.

It also suggests solving the problem by deriving height as well as plan by acoustic ranges after calibration, at points midway between the transponders, and making sure that sea-level does indeed come out as sea-level.

If tempted to dismiss vertical scale as of no interest, one need only rotate the originally vertical section about the transponder baseline to see that offline one still has a constant (1 + 2k) scale parallel to the baseline, but the large vertical scale error converts more and more to a *horizontal* scale error at right-angles to the baseline, so as to systematically degrade the least squares plan solution.

The running mean

A feature of the Oasis system, which is also in much other satellite receiver software, is what one may call the fallacy of the "running mean" where a cumulative series of solutions is produced with accompanying graphs converging convincingly with smaller and smaller variations to the final solution.

This is also found in the current UKOOA procedures guide : "A minimum of 30 3-dimension (3D) passes should be recorded or such number as will result in a convergence to within an oscillation amplitude of 5 metres in latitude and longitude and 2 metres in antenna height...".

The fallacy is in the complete dependency of the appearance of the result on the order of the data accumulation. Thus if 30 UKOOA passes had a latitude mean of 10 metres above an arbitrary datum at pass 26 followed by :

	Individual value	Running mean
Pass 27	– 125 metres	5 metres
Pass 28	285 metres	15 metres
Pass 29	– 275 metres	5 metres
Pass 30	155 metres	10 metres

it would be acceptable, but not if these passes were in a different order or distributed earlier in the series.

While the cumulative solutions will often not be straight unweighted means but weighted means or fresh least squares computations, this first order effect only changes the argument in detail – by "unscrambling" the series one can still reconstruct a set of pseudo-results whose means give the cumulative solutions, and test these for spread, skewness, etc., as if they were genuine.

Smoothing

My first introduction to the wider topic of offshore smoothing (of which the flat-earth society were early exponents) was when a colleague of long standing remarked that he was not unduly depressed at some alarming peaks in navigation plots but surprised that they had reached the client in that form.

The technique when properly controlled is invaluable for extracting meaningful "signal" from unwanted "noise" but there is the psychological problem that the contractor wishes to produce a pleasing result in a competitive world and the client also wishes to be given one.

All that can be usefully said is that:

(a) Every attempt should be made for a permanent record of the original raw data.
(b) If this is impossible – one often has smoothing at acquisition stage to reduce the data to manageable proportions – then every effort should be made to agree and record what is done by the operator in the field (smoothing parameters, etc.).
(c) The "earliest" possible generation of the data should then be recorded as before.
(d) Any techniques to improve the presentation should again be agreed and what has been done recorded – including intermediate results even if they are not attractive.

It is a basic principle of all land and hydrographic surveying that the field-books "warts and all" are sacrosanct and since, with apologies to the author of Genesis (and of Beyond the Fringe): "My Brother Esau is an hairy Man, but I am a smooth Man", on this occasion Esau was right.

ACCURACY AND REPEATABILITY

What is possible

Thus one can see that in round terms a formal reading accuracy of:

(a) some 2 to 5 metres for typical line of sight system;
(b) anything from 50 metres down to (with increasing effort) 10 metres for beyond line of sight systems;

is usually subject to predictable and unpredictable systematic and random error which can degrade these figures by anything up to 50 % – or even more.

The systematic errors may be:

(a) peculiar to a particular area (wrong 'C – O', etc.) – they will not affect repeatability for the same survey system but may degrade relative accuracy depending on the size of the survey area and the rate of change of the error across it;
(b) peculiar to a particular area and time (unusual met. conditions, etc.) – repeatability will suffer and relative accuracy may be affected as before

but absolute accuracy in relation to true survey datum onshore will always be degraded.

With the random errors, one must beware of the statistical trap of assuming that more observations will inevitably improve results.

There is the old chestnut of the Eskimo standing outside his igloo who can tell the azimuth of a line to within 20 degrees by looking at it: one then asks 100 Eskimos and means the answer, to an accuracy of 2 degrees – while 10,000 Eskimos will yield 12 minutes of arc and so on. Clearly there is a limit beyond which one cannot go.

What is needed (a user decision)

From what has been said of accuracies at the various stages of oilfield exploitation :

Deep seismic models.....	3 to 88 metres
Shallow seismic models ..	2 to 15 metres
Down-hole surveys	2 to 4 metres
Wellhead recovery.......	2 metres, say
Unitisation	(1 metre)
Pipeline connections	20 centimetres, say

the basic principle in land and hydrographic surveying, that survey should aim to be an order of accuracy better than the system it supports, suggests at first sight that offshore positioning and navigation should seek the last refinement of accuracy regardless of expense – bearing in mind that the positioning cost is usually so small in relation to overall costs that it can be considered as "noise" in the overall financial equation.

In fact, if the surfaces to be seismically modelled are gently sloping and lack near-vertical features, some reduction in positioning accuracy is indeed possible.

If a reflector slopes t° to the horizontal, a surface positioning horizontal error with a component of h metres in the down-slope direction results in a vertical seismic error of:

$$h \tan t \text{ metres}$$

with comparable "smear" in the seismic section if the error is random.

Hence for hydrocarbon traps formed by simple structural folding (domes, anticlines, etc.), an undistorted seismic model only needs *relative* surface positioning accuracy of:

Reflector	Relative surface positioning accuracy
1°	172 metres (to 5 kilometres)
2°	86 metres (to 2.5 kilometres)
5°	34 metres (to 1 kilometre)
10°	17 to 499 metres
20°	8 to 242 metres
40°	4 to 105 metres

On the other hand seismic surveys of structures with vertical features such as faults, dikes, intrusions, etc., especially if they are near the intended drilling area, need as much surface positioning accuracy as can economically be justified – see later.

Repeatability is required (to a lower order of accuracy) for relating similar features on different seismic surveys and for positioning drilling rigs (100 metres, say), while absolute accuracy on an onshore survey datum, although not vital unless the field overlaps block boundaries or international median lines, is the only safe criterion, unless the same survey system with the same parameters is certain to be used for positioning at all stages of development and appraisal.

Financial and time cost considerations

The fact that survey positioning charges are so low, in relation to the offshore activities they support, carries two dangers of opposite polarity :

(a) To play safe, by assuming unlikely combinations of equipment failure, crowds the navigation area with redundant machines recording data which will never be used and diverts attention from the primary navigation system in actual control so that :
  i) an error condition goes unnoticed;
  ii) a software or hardware parameter fed in unrecorded defeats the whole operation;
  iii) a genuine observation (such as a change of course or speed) is treated by the operator, or the software, as an error and "adjusted out";
  iv) essential results are not recorded.

(b) To treat positioning and navigation as the "poor relation", with inadequate equipment and inexperienced operators, can be equally disastrous.

Positioning is, in fact, not as cheap as it seems for if time is spent to the exclusion of other work by a positioning failure or a system requiring extensive calibration before anything else can begin, the cost of waiting, or putting into port or repeating expensive seismic surveys or delaying the positioning of a rig or platform can be orders of magnitude greater than the nominal positioning charges themselves.

Decisions in this area require disciplined systems analysis to assess realistic probabilities and solve the linear programming problem in which positioning costs themselves are one relatively minor factor.

FUTURE SATELLITE DEVELOPMENTS

North sea datums

Up to the end of 1975 the satellite datums were accepted as :

(a) WORLD GEODETIC SYSTEM 1972 ($a = 6378135$, $1/f = 298.26$)

This universal datum (WGS72) was intended to have its axes parallel to those of "well-behaved" national and international terrestrial survey datums, so that to convert from geocentric cartesians (X, Y, Z) on WGS72 to European Datum (ED50) one applied the transformation :

$$dX = 84 \text{ metres}$$
$$dY = 103 \text{ metres}$$
$$dZ = 127 \text{ metres}$$

(b) NAVAL WEAPONS LABORATORY 9D ($a = 6378145$, $1/f = 298.25$)

This military datum (NWL9D) was and effectively remains that of the precise ephemeris satellite doppler not normally available to civilian users. Before converting to cartesians one had to rotate by 0.26 seconds in longitude and subtract 5.27 metres from spheroid height – the resulting cartesians were then identical with those of WGS72.

(c) APPLIED PHYSICS LABORATORY 4.5 ($a = 6378137$, $1/f = 298.25$)

This universal datum (APL4.5) was that of the broadcast ephemeris satellite doppler. Its origins were obscurely documented, and practice in the North Sea area was to treat its cartesians as if they were identical with those of NWL9D.

On 12 December 1975 it was announced that broadcast ephemeris was now on WGS72 and results derived were treated as such.

Recent discussion suggests that :

(a) Broadcast ephemeris was not converted to WGS72 but in effect became NWL9D.
(b) WGS72 (and hence NWL9D) and North American Datum (NAD27) all require a longitude rotation of about 0.8 seconds to bring them into sympathy with the latest astronomical reference system.

Since there is no reason to suppose that ED50 has not got its axes parallel to those of NAD27 (such Laplace stations as each have predate the 1968 change in definition of mean pole and meridian) and since the need is to relate broadcast ephemeris to existing ED50 and not to the new astronomical system, the current UKOOA recommendation for North Sea use is to treat broadcast ephemeris as NWL9D and convert to WGS72, and thence to ED50, as above – exactly as if it were still APL4.5.

An international proposal is in hand to relate NWL9D to ED50 in the North Sea area by means of a shift, scale and longitude rotation derived from data effectively lying within a 900 kilometre radius circle centred in the North Sea.

This I think wrongheaded since :

(a) The scale change (– 1.8 parts per million) compared with an increment of vertical datum shift in the centre (– 11.6 metres) would differ at the edge of the area by only :
0.1 metres vertical
– 1.6 metres horizontal (radial from the centre).

(b) The original – 5.27 metres spheroid height change gives, in the same terms :
0.05 metres vertical
– 0.73 metres horizontal.

(c) The area covered by the data forms an annular ring with the North Sea as a hole in the middle – so that the scale versus datum shift discrimination depends on points near the inside and outside circles bounding the annulus.

(d) No account is taken of the 3 parts per million scale error in the SN70 coordinates in U.K. and so the data-set is not homogeneous.

(e) JENKINS and LEROY at Austin said of the EROS-DOC 7-parameter fit over twice the area (Finland to Spain and Greece): "The differences are probably caused by the fact that their data were localised to the European Continent, with likely conditioning problems"

but we must live with the proposal as best we may.

UKOOA are in fact seeking a via media by adopting the five parameter precise ephemeris transformation, but applying it to all satellite observations in the North Sea area rather than as suggested having a second separate three parameter shift for broadcast ephemeris – see Appendix A for the relevant extract from the proposed recommendation to UKOOA users.

Waiting times

While the general principle holds that a given satellite can be observed more often at higher latitudes than at lower, there is an interesting "resonance" around latitude 41°13′ N (or S) which affects waiting time.

Referred to the descending longitude of pass 1 ("pass 1D") one has the following successive longitudes:

Latitude	Pass 2D	Pass 8A	Pass 9A	Pass 10A
50	– 26°45′	– 1°18′	– 28°03′	– 54°48′
40	– 26°45′	(– 359°49′)	– 26°34′	– 53°19′
30	– 26°45′	(– 358°20′)	– 25°05′	– 51°50′
20	– 26°45′		– 23°36′	– 50°21′
10	– 26°45′		– 22°07′	– 48°52′
0	– 26°45′		– 20°37′	– 47°22′

Again, if one assumes 15° and 70° to be the limits of acceptable angle of elevation at closest approach, the limiting longitudes referred to that for + 15° are:

Latitude	+ 70°	– 70°	– 15°	Elevation
50	– 25°26′	– 34°54′	– 60°18′	
40	– 21°17′	– 29°09′	– 50°25′	
30	– 18°48′	– 25°43′	– 44°31′	
20	– 17°19′	– 23°41′	– 40°59′	
10	– 16°31′	– 22°35′	– 39°06′	
0	– 16°16′	– 22°14′	– 38°30′	

Thus, at "resonant latitude" 41°13′ where passes nD and (7 + n)A coincide for all n, a particular satellite overhead (and unobservable) at 2D will be :

(a) unobservable overhead at 9A
(b) unobservable (elevation + 13°43′) at 1D, 3D, 8A, 10A
(c) observable (39°22′) at 15D, 22A and (– 33°44′) at 16D, 23A
(d) marginally observable at 28D, 35A but not again until 42D.

and a period of 10 days (136 passes) centred about 2D yields just 16 good (and 24 marginal) passes – bunched in 4 periods of 14 hours (4 good passes each) at 34-hour intervals but with a longer (50-hour) interval around the overhead pass 42D.

This may become more troublesome in these latitudes in 2 or 3 years' time, when 3 of the existing 5 satellites will become very closely bunched – in September 1982 their longitudes referred to the first point of Aries (right ascensions of ascending node) will be

30140	143.2°
30200	134.8°
30110	156.6°

Navstar Global Positioning System

Much interest has focussed on this coming system which is planned to give an instantaneous (or almost instantaneous) position good to 10 metres or better, with 4 satellites above the horizon at once. However, it is understood that the programme has already slipped a number of years and may slip further – which will presumably similarly extend the life of the present TRANET system. There is also the problem of a degraded accuracy being offered for civilian users – the figure of 200 metres has been quoted – and in the light of what has been said earlier, much would depend on whether there is a degradation of absolute accuracy only – otherwise this would be quite useless for offshore work.

Acknowledgements

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APPENDIX A

Single point fixes in U.K. offshore waters

As a result of discussions in 1979/80 between six of the interested national survey organisations around the North Sea area, recommended procedures for converting single point doppler satellite fixes from satellite datum to European Datum 1950 were set out in detail in Ordnance Survey Professional Paper new series No. 30 of February 1981.

UKOOA recommendations are now that both broadcast and precise ephemeris observations should be reduced to ED50 as follows :

Convert the raw X, Y, Z output of the doppler receiver to latitude, longitude and spheroid height using the NWL9D spheroid :

$$a = 6378145 \text{ metres}$$
$$1/f = 298.25$$

Add 0.97 second of arc to the longitude and subtract 11.48 metres from the spheroid height (i.e. a scaling of − 1.8 parts per million) before converting back to X, Y, Z coordinates using the same spheroid, and then apply the datum shift :

$$dX = +\ 89.5 \text{ metres}$$
$$dY = +\ 93.8 \text{ metres}$$
$$dZ = +127.6 \text{ metres}$$

See sample computation attached, as well as a standard proforma to be used when reporting satellite doppler observations, especially when these are to be supplied to the Ordnance Survey or other national survey organisations.

Translocation fixes in U.K. offshore waters

This technique requires that established European Datum coordinates of the base stations used onshore be transformed to the common ED50 offshore system. This is done as follows :

(a) *United Kingdom and Eire base stations*

Rotate the European Datum system for each base station by adding 0.24 seconds of arc to the longitude and apply a scaling of + 1.3 parts per million by adding 8.29 metres to the spheroid height, convert to X, Y, Z coordinates using the International (Hayford) spheroid :

$$a = 6378388 \text{ metres}$$
$$1/f = 297$$

and then apply the datum shift :

$$dX = -\ 5.4 \text{ metres}$$
$$dY = -\ 3.8 \text{ metres}$$
$$dZ = -\ 6.7 \text{ metres}$$

to arrive at the common ED50 offshore system version of the original European Datum position.

(b) *Norway base stations*

Rotate the European Datum system for each base station by subtracting 0.52 seconds of arc from the longitude and apply a scaling of + 1.7 parts per million by adding 10.84 metres to the spheroid height, convert to X, Y, Z coordinates using the International (Hayford) spheroid :

$$a = 6378388 \text{ metres}$$
$$1/f = 297$$

and then apply the datum shift :

$$dX = - \ 5.9 \text{ metres}$$
$$dY = + \ 6.2 \text{ metres}$$
$$dZ = - \ 10.4 \text{ metres}$$

to arrive at the common ED50 offshore system version of the original European Datum position, as before.

(c) *Germany, Denmark and Netherlands base stations*

Rotate the European Datum system for each base station by adding 0.03 seconds of arc to the longitude and apply a scaling of − 2.3 parts per million by subtracting 14.67 metres from the spheroid height, convert to X, Y, Z coordinates using the International (Hayford) spheroid :

$$a = 6378388 \text{ metres}$$
$$1/f = 297$$

and then apply the datum shift :

$$dX = + \ 9.8 \text{ metres}$$
$$dY = + \ 1.1 \text{ metres}$$
$$dZ = + \ 12.8 \text{ metres}$$

to arrive at the common ED50 offshore system version of the original European Datum position, as before.

The corrections derived by making the X, Y, Z output at the base station doppler receivers conform to these E.D. values are then applied to the X, Y, Z output of the doppler receiver at each unknown station to derive final European Datum 1950 X, Y, Z coordinates. These may be converted to latitude, longitude and spheroid height on ED50 using the International (Hayford) spheroid :

$$a = 6378388$$
$$1/f = 297$$

One way of achieving this agreement is to treat the doppler observations at both base and unknown stations as separate single point fixes and so apply at the outset the single point fix transformation (without the final datum shift) described earlier in these specifications; this has the merit of injecting the European Datum (North Sea) orientation and scale into the translocation transfer.

In view of the variety of editions of computer software available to users (some of which may already include the above, or different, transformations) it is essential that results at all stages of datum shift or transformation should be fully listed in final reports of doppler satellite operations (or at the very least, the original raw output in three-dimensional cartesian coordinates X, Y, Z should be supplied). This is particularly important if other translocation techniques are used which do not preserve the orientation and scale of the translocation transfer as described above but allow the orbit to deform, stretch or rotate during the computation.

Note finally that while these translocation formulae can equally be applied elsewhere in the North Sea, users outside U.K. offshore waters may well wish to seek confirmation of the procedure to be adopted from the appropriate foreign authority.

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ROPES AND KNOTS

The cord is the oldest surveying tool. In fact, it is a thing of many uses. No wonder that the skill of making cords and ropes from twisted fibers has been known for many thousands of years. Extant evidences are fishtrap nets of eight thousand years ago, the hauling of huge stone blocks on ancient tomb pictures, twisted rope bridles on animals, rope bridges and hunters' rope traps in ancient European and South African cave drawings, etc. Its age-old use for surveying is seen on a wall painting of an ancient Egyptian tomb (– 1400) where men equipped with ropes and writing material are shown measuring a grain field. A reel of rope of a specific length is mentioned in various ancient documents as a length unit. Laying the cornerstone for an Egyptian temple was a royal function and the ceremony is mentioned in documents and depicted in paintings: a king and a goddess stretch a cord between them to establish the base line, and drive stakes into the ground to fix the corners. Or the king sights the polestar through a cleft stick and the goddess holds the cord which will lay down a north-south line as the reference for the other corners. In Lagash, Sumer, a tablet was found dating from – 3100, which shows also a Sumerian king laying the cornerstone.

"To stretch the rope" thus meant surveying for distance as well as direction; and tying knots into it at certain intervals will fix a length, as is familiar to us from the nautical knot, a unit for a ship's speed per hour. Knots and systems of knotted strings played a role in several cultures, not only as symbols of magic power and amulets as antidotes, but as a means, e.g., of counting the days before an awaited event by opening one knot as each day passed (*Herodotus*, IV, 98), of keeping tax records and business accounts, giving tax receipts, and also noting down the measurements of a survey, etc. The Incas of Peru had no writing but managed with elaborate systems of knotted strings, called *quipus* (meaning "knots" in their language) which name has been adopted for similar systems in other cultures. A quipu consisted of a horizontal main cord from which several strings in various colors dangled at various intervals. Knots tied into these strings varied in distance from the main cord, in size, and type of knotting. The possible combinations of all these variables under an agreed code provided mnemonic aids for the *quipucamayas*, the Inca government record keepers, to maintain information on administrative laws, surveys, historical traditions as well as to keep numerical accounts.

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