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REDACTIECOMMISSIE

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A PORTABLE RESPIRATORY RATE RECORDER FOR ATHLETES

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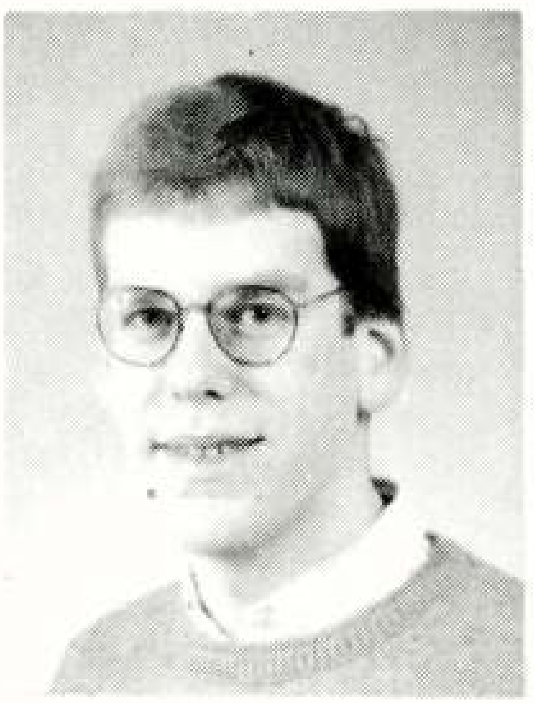

Abstract

This article describes the development of a portable respiratory rate recorder (PRRR) for athletes, at the Eindhoven University of Technology. Respiratory rate can be used to detect the anaerobic threshold of athletes.

The PRRR can be used to measure the respiratory rate of athletes during exercise in the field, whereas existing devices can only be used in a laboratory. The measured respiratory rate is shown on a liquid crystal display and stored in memory. When the measurement is completed, the PRRR can be connected to a personal computer, to load the results for further analysis.

A pressure sensor mounted in a flexible belt around the chest of the athlete is used to measure the respiratory signal. The hardware of the PRRR consists of a Philips microcontroller with some supplementary circuits. The software is written in the 'C' language.

In a final evaluation under laboratory conditions, the developed portable respiratory rate recorder has been tested with four subjects. The values measured during the exercise test were compared with the values measured with a professional measurement system. This comparison shows that the portable respiratory rate recorder gives reliable values for the respiratory rate of an athlete.

1 Introduction

As you will know from your own experience, the respiratory rate increases as one exercises. This is an example of the phenomena that are studied in the field of exercise physiology. Professor H. Kuipers of the Group of Movement Sciences of the University of Limburg (RL) studies the variability of physiological responses to exercise. Interested readers can find more in [1] and [2]

The "fuel" the human muscle needs, is an energy-rich phosphate called ATP. This ATP can be generated in two ways. The first way consists of the breakdown of glucose with the use of oxygen in the blood. The uptake of oxygen by the lungs is limited. When the maximum is reached and still more power is needed, the second way to produce ATP is activated. This so called anaerobic metabolism consists of the breakdown of glucose to lactic acid (lactate). The anaerobic energy delivery can only be used for a few minutes because it causes the intracellular pH to drop. In this situation the function of the muscle decreases and the desired power can no longer be produced.

1.1 *The use of respiratory rate to detect the threshold*

One of the aims of prof. Kuipers' research project is to find a method to detect when the athlete 'switches' from aerobic to anaerobic energy delivery during activities which last longer than ten minutes. One approach is the detection of the ventilatory threshold. At the anaerobic threshold the athlete takes up his maximum amount of oxygen. The oxygen uptake can be determined by measuring the difference in concentration of oxygen in the inhaled and exhaled air and by multiplying this by the inhaled volume of air per minute. The difference in concentration of oxygen depends on which shape the athlete is in. Because the tidal volume of the lungs can be assumed to be constant under these circumstances, the respiratory rate can be used to determine the oxygen uptake. This means that the respiratory rate can be used to detect the anaerobic threshold. The advantage of using the respiratory rate is that it can be determined by measuring the perimeter of the chest. This means it can be used real-time, in a situation outside the lab.

2 Requirements of a portable respiratory rate recorder (PRRR)

2.1 *The Functions of the PRRR*

Figure 1 shows an athlete with a PRRR :

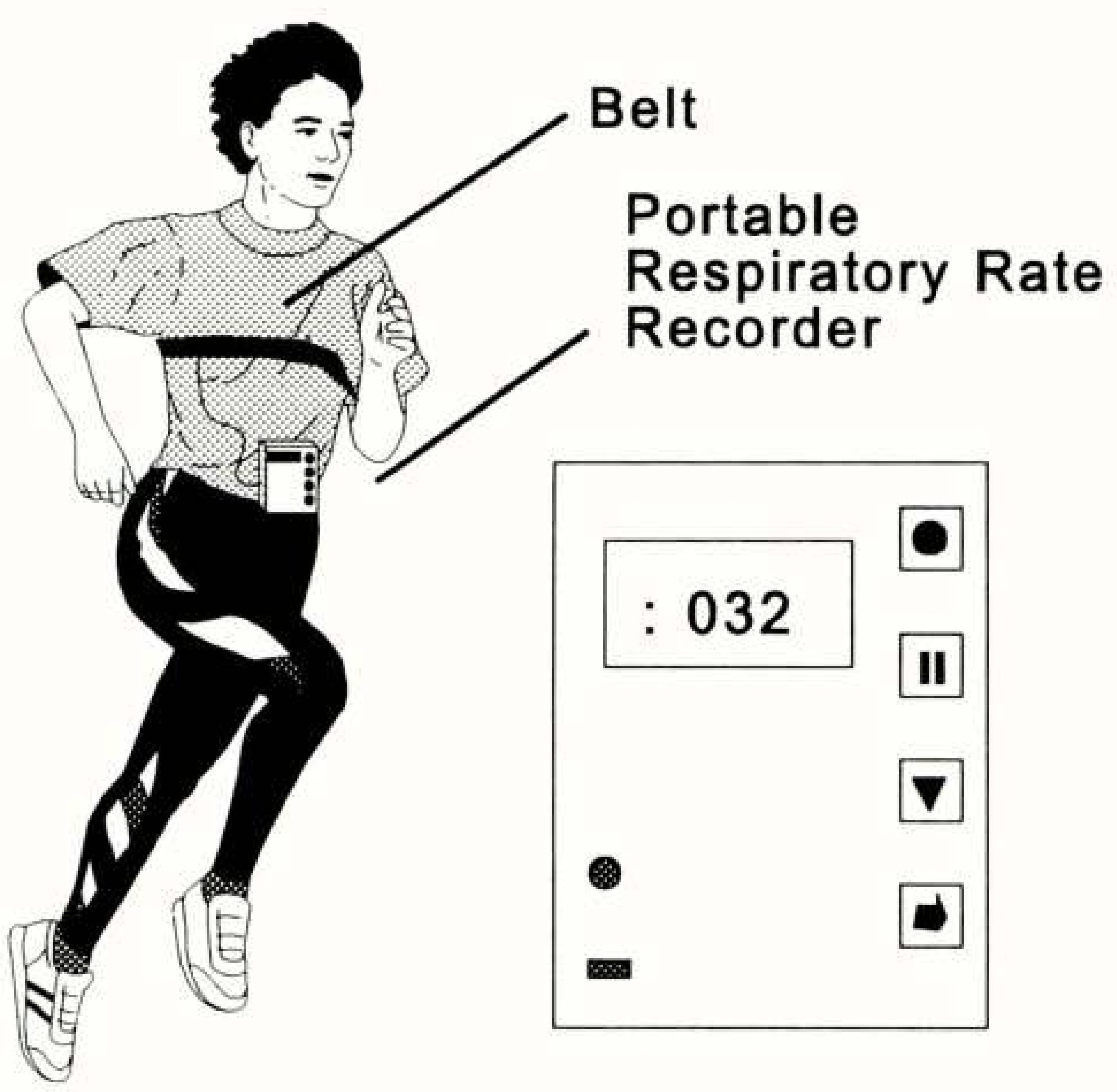

Figure 1. Portable respiratory rate recorder

The functions of the PRRR are :

- Displaying and recording the value of the respiratory rate of an athlete during exercise. When the measurement is completed these values can be transmitted to the serial port of a personal computer for further analysis.
- Producing an acoustic alarm when the value of the respiratory rate is not between a predetermined upper and lower limit.

To carry out these functions, the PRRR should be a small and light device. It has to be resistant to mechanical shocks and against humidity. The device should be battery powered. More about the user-interface can be found in [3].

2.2 *Technical Data*

- Frequency range : 6 - 120 resps./ min. (0.1 - 2 Hz)
  Typical range for athletes : 10 - 40 resps./min. (0.2-0.7 Hz)
- Accuracy : 2.5 % of the full scale (= 3 respirations/min.)
- Respiratory rate calculated, displayed and stored twice per minute
- Maximal recording time 15 hours
- Minimal data storing time 1 week

3 Determining the respiratory rate of an athlete

3.1 *Measuring the respiratory signal*

In order to convert the respiratory signal of the athlete into an electrical signal, the athlete wears a flexible belt around the chest. Figure 2 shows the prototype. The basic component of this belt is a pressure sensor. The electrical resistance varies from 2 MS when not pressed, to 1 kS when pressed. The material is resistant against humidity.

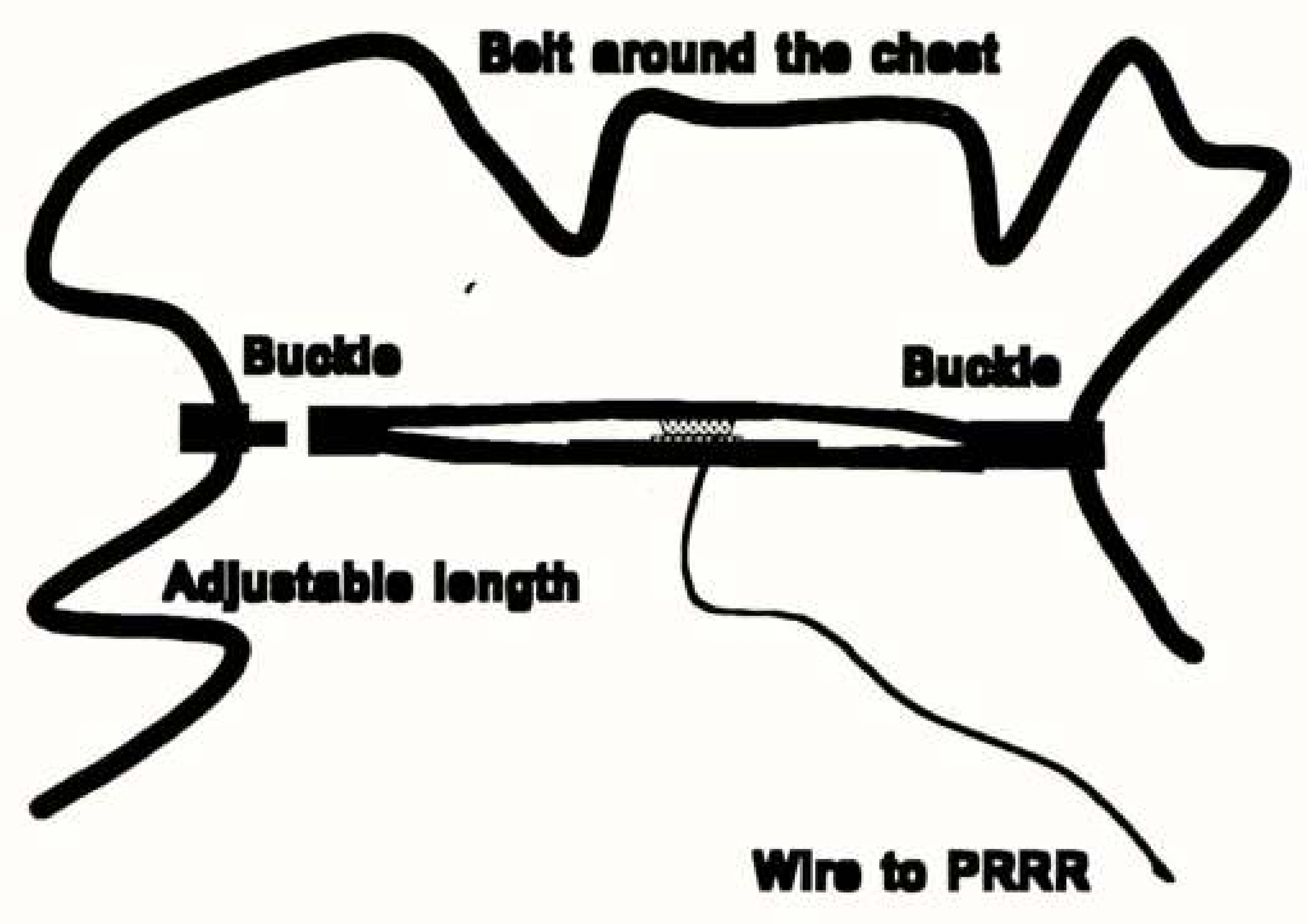

Figure 2. The belt

Two stainless steel plates are attached to a double piece of flexible belt. This piece is connected with two buckles to a single flexible belt around the chest of the athlete. The pressure sensor is mounted on the plate at the side of the chest. The force from the varying perimeter of the chest will now push the two plates together. To place this force on the pressure sensitive surface of the sensor, a small block is mounted on top of the sensor.

3.2 *Frequency analysis of the respiratory signal*

The Portable Respiratory Rate Recorder (PRRR) has to determine the respiratory rate, in other words the frequency of the measured signal. The method is a variant of the Orthogonal Search Method (OSM). In order to customize the method for our PRRR the following assumptions were made:

- The value of the respiratory rate is in the range of 6 to 120 respirations per minute, which means that the maximum frequency is 2 Hz.
- The respiratory signal can be approximated by a

single sinewave, with the parameters frequency, amplitude and phase.
- The signal does not have a DC-component.

The fitting is optimized by the least mean squared error method. The developed algorithm is implemented in Turbo Pascal and thoroughly tested with measured respiration signals. The combination of a 5 Hz sampling frequency and an interval length of 20 seconds has resulted in accurate values of the respiratory rate.

4 Hardware overview

Figure 3 shows a block diagram of the PRRR :

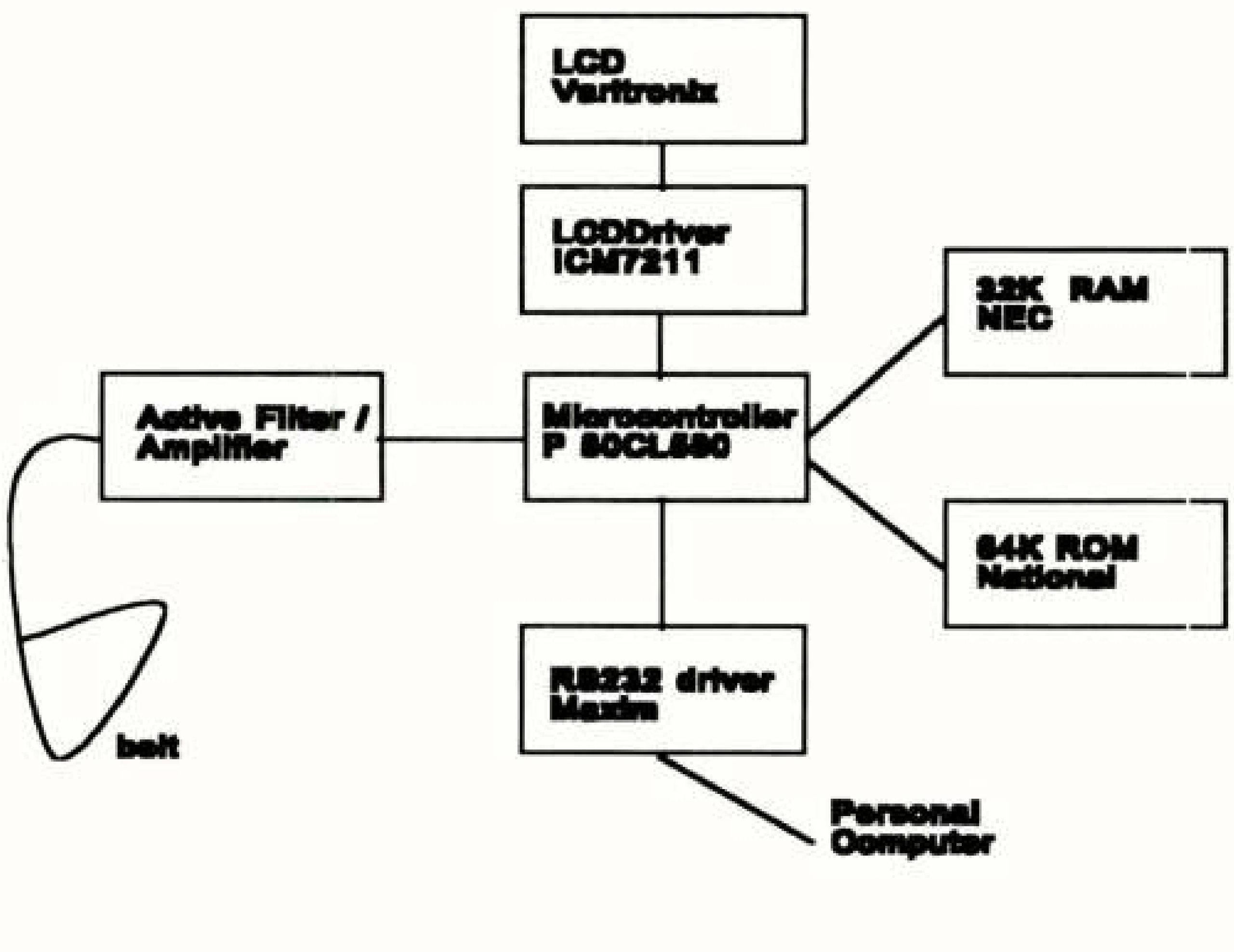

Figure 3. A block diagram of the PRRR

4.1 *Active filter/Amplifier*
The active filter/amplifier converts the electrical signal from the belt into a signal that is suitable for the A/D converter. This custom designed filter consists of a pre-amplifier, a bandpass filter, an adjustable amplifier and an anti-aliasing filter.
4.2 *Microcontroller P80CL580*
The core of the PRRR is an 8-bit Philips 80CL580 microcontroller. In this design the microprocessor controls the measurement and calculates the value of the respiratory rate of the measured breathing signal. This type has a built-in A/D converter.

4.3 *Memory*
The 32 kByte Random Access Memory (RAM) is used to store the calculated values of the respiratory rate and the variables that are used in the programme. The 64 kByte Electrical Programmable Read Only Memory (EPROM) is used to store the programme of the microcontroller.

4.4 *RS-232 driver*
The RS-232 interface works with levels of +12 V and -12 V. The microcontroller works with 0 V and the supply voltage (4.5 V in the prototype). The Maxim 232 driver is used to match these levels.

4.5 *Liquid Crystal Display (LCD)*
The LCD shows the calculated respiratory rate or another message to the athlete. The Maxim ICM7211 drives the LCD. The combination of LCD and driver has three hexadecimal digits. The seven-segment characters are 1/2 inch high.

5 Software overview

5.1 *Software development in 'C'*
The development of the software started in parallel with the design of the hardware. The programme is developed in the 'C' language. This made it possible to test parts of the programme on the PC, even before the prototype of the PRRR was ready.

5.2 *The structure of the programme*
The operation of the programme is straightforward. The software consists of four functions and some supplementary functions. Figure 4 shows the overall design of the programme.

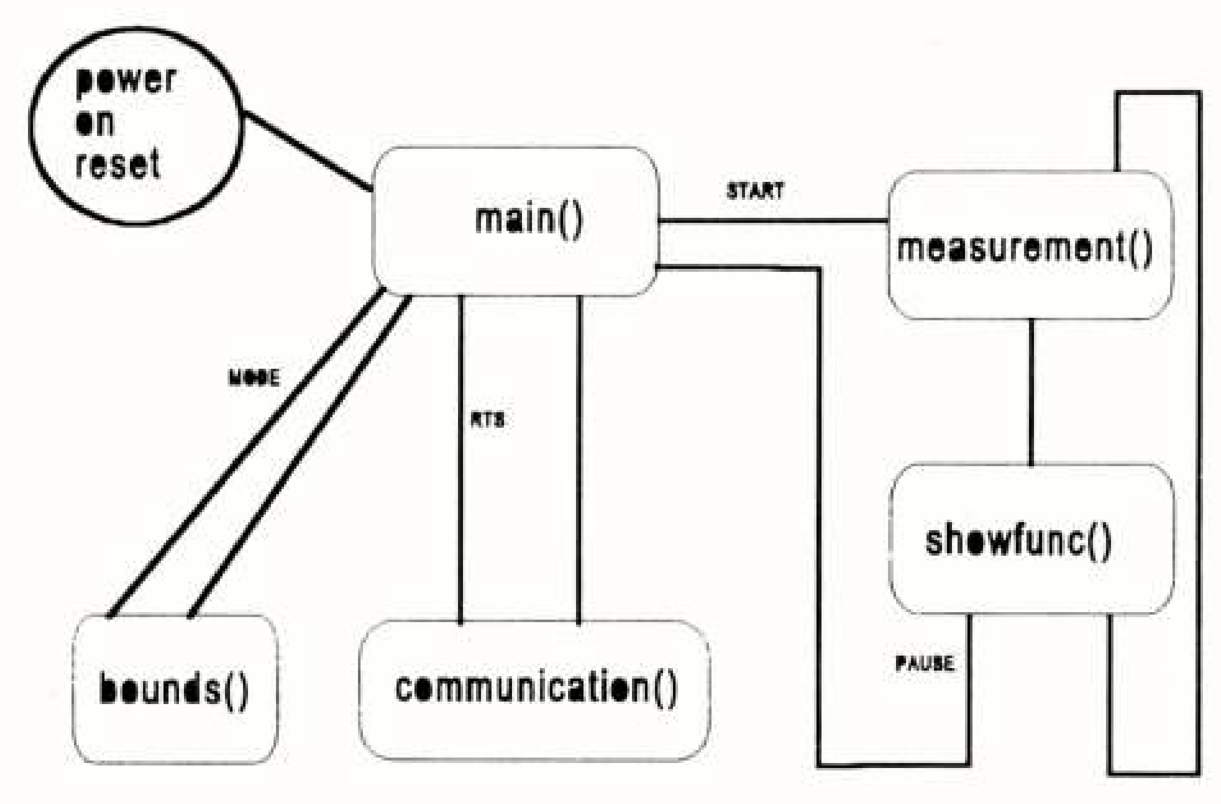

Figure 4. Chart of the program structure

When the PRRR is switched on, the microcontroller is being reset. This is called the power-on-reset. From here the main() function is started. The main() function waits until the user presses a button or starts the communication programme on the personal computer. The bounds() function enables the user to adjust the lower and upper limit of the respiratory rate. When a measured respiratory rate is not within these limits, the PRRR will produce an alarm. The measurement() function samples 20 seconds of the respiratory signal. The samples are stored into an array. After this, the showfunc() function is started. This function calculates the value of the respiratory rate from the datasamples in the array. The communication() function sends the measured data to the serial port with a rate of 9600 Baud.

6 Evaluation

6.1 *Procedure of the Final Test*
The final test took place at the group of Movement Sciences at the department of Physiology at the University of Limburg (RL). Four well-trained students of Movement Sciences volunteered to be subjected to the

test. The testing took place on an electronically braked cycle ergometer. During exercise the respiratory rate of the subject was simultaneously measured in two ways :

- The subject breathed through a low resistance breathing valve connected to a face mask. An automatic gas analysing system was used to measure respiratory rate. The accuracy of this professional system is two resps./ min.
- The subject had a flexible belt around the chest, connected to the portable respiratory rate recorder. The PRRR determines the respiratory rate within one respiration per minute.

6.2 *Final Test Results*

When studying the test results, it should be noted that the measurement methods differ and that intervals are not exactly synchronous. This means the results must be considered with caution. A difference of three respirations per minute between both measurements is not significant. The required accuracy of the PRRR is also three respirations per minute. This means that values with a difference of six respirations per minute are still within the requirements. From the testresults it appeared that the percentage of the measured values which differ six or less is in the range of 80 % up to 94 %. Because in this test only four subjects were measured, further testing is suggested to get reliable conclusions. The PRRR should also be tested with subjects during other kinds of sports, for example running or speed skating.

7 Conclusions and suggestions for future improvements

- The developed sensor is a cheap and suitable sensor for measuring the respiratory rate of an athlete. Further development and testing of this sensor is recommended.
- The developed prototype of the portable respiratory rate recorder is tested and compared with a professional measurement system. This test shows that the respiratory rate recorder gives reliable results. Further testing of the PRRR is required.
- The developed prototype satisfies most of the requirements. Points that can be improved are : The size of the device and the energy consumption.

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TOMOGRAFIE VAN DE IONOSFEER

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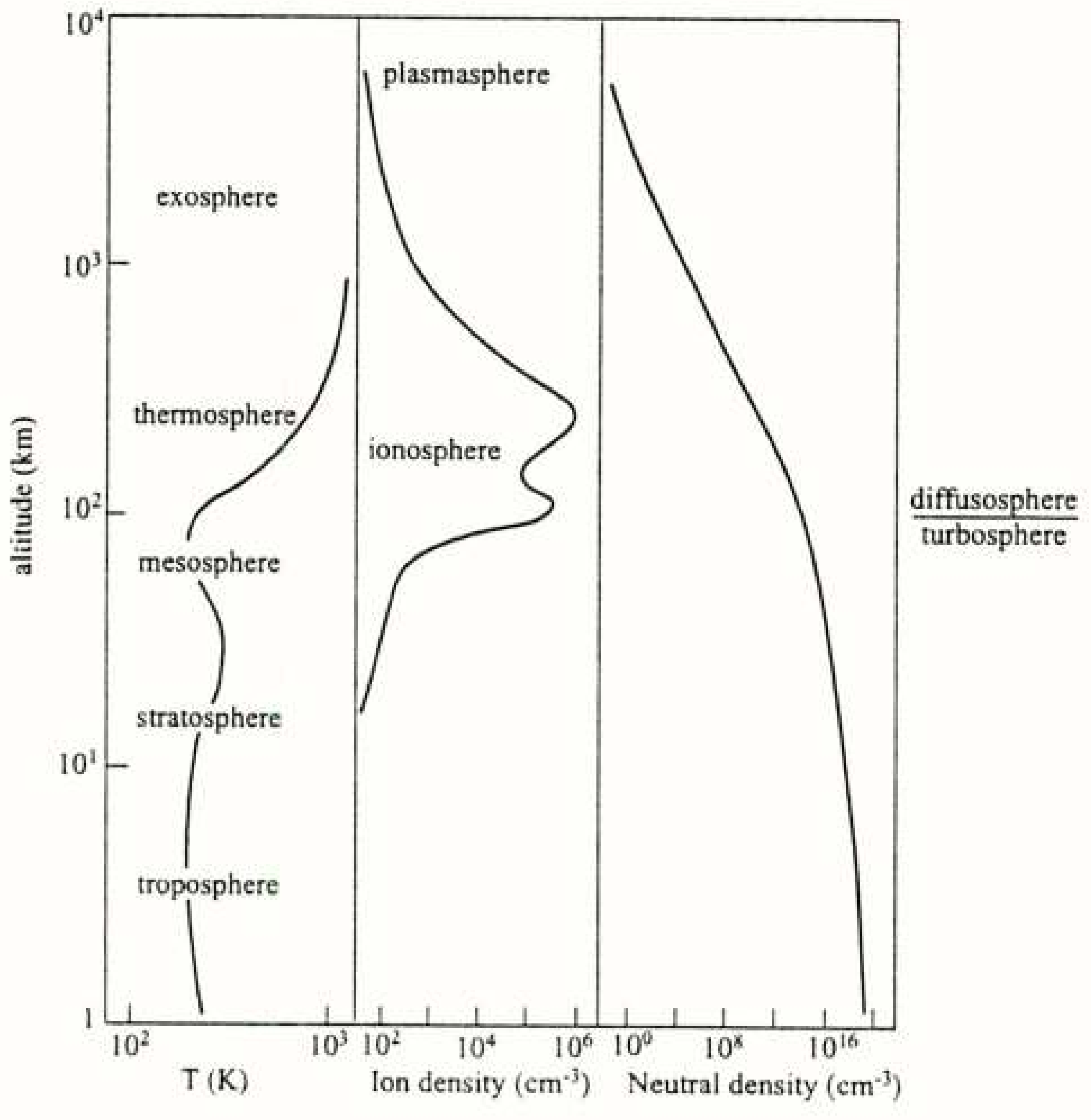
Abstract

Tomography of the ionosphere is a new and inexpensive method to image electron density in vertical cross-sections of the ionosphere.
This paper summarizes the need for such a technique, its principles and some of its theoretical aspects; it ends in the description of an experiment with five satellite-receivers along the Eindhoven meridian, from Harlingen to Marseille.

De ionosfeer

Door de zwaartekracht heeft de atmosfeer van de aarde een gelaagde structuur. Met wat goede wil is het mogelijk om afzonderlijke lagen te onderscheiden.
Het meest bekende criterium voor zulk onderscheid is de temperatuur.
Hierop is de indeling troposfeer, stratosfeer, mesosfeer en thermosfeer gebaseerd, waar de temperatuur met de hoogte afwisselend af- en toeneemt (zie figuur 1).



Figuur 1: Schematische voorstelling van de thermische structuur, de dichtheid van geioniseerde deeltjes en de dichtheid van neutrale deeltjes in de atmosfeer van de aarde.

Een ander criterium is gebaseerd op de mate waarin vrije ladingen en het magneetveld het fysisch gedrag van de atmosfeer bepalen. Zo is de ionosfeer gedefinieerd als dat gedeelte van de atmosfeer, waar de voortplanting van radiogolven merkbaar wordt beinvloed door de aanwezigheid van vrije ladingen.
Elektronen en enkelwaardig positieve ionen ontstaan doordat energierijke straling van de zon de atmosferische gassen gedeeltelijk ioniseert.
Hun aanwezigheid verandert de brekingsindex voor radiogolven.

De ionosfeer strekt zich uit van ongeveer 80 tot 1000 kilometer hoogte.
Rond de 300 km is de elektronendichtheid maximaal, ongeveer 10^6 cm^{-3}. Op deze hoogte is atomair zuurstof het belangrijkste neutrale deeltje en O^+ het belangrijkste ion.
De ionisatiegraad is hier nog laag, minder dan 10^{-3}, maar neemt toe met de hoogte. Pas op 3000 km hoogte, in de plasmasfeer, is sprake van volledige ionisatie.
Het behoeft geen betoog dat de elektronendichtheid sterk van de hoeveelheid invallende ioniserende straling afhangt, en daarom varieert met de zonnecyclus, de seizoenen en het dag-nacht ritme.

Wat is het belang van de ionosfeer?
Allereerst filtert het fotoionisatie-proces de gevaarlijke kortgolvige straling uit het zonlicht. Dit betreft het ioniserende gedeelte van het zonnespectrum, tot en met ruwweg de Lyman α lijn bij 122 nm, met een totale flux van ongeveer 8 mW m^{-2} [1].
Ter vergelijking: O_2 en O_3 absorberen door fotodissociatie de straling tussen Lyman α en 300 nm.
Je zou dus kunnen stellen dat de ionosfeer even belangrijk is als de ozonlaag! Dit is echter niet het geval, om-

dat het vermogen geabsorbeerd in de ozonlaag enige honderden malen groter is dan dat in de ionosfeer. Ook kan er nooit een bedreigend gat in de ionosfeer ontstaan, omdat de buitenste luchtlaag sowieso geioniseerd wordt. De ionosfeer zal dus pas verdwijnen als de hele atmosfeer verdwijnt.
Hoewel van vitaal belang, is het duidelijk dat dit aspect van de ionosfeer geen aanzet geeft tot onderzoek.

Aan de andere kant van het spectrum zit meer NWO-beleidsruimte. Zoals gezegd beinvloedt de ionosfeer de voortplanting van radiogolven. Dit is ongunstig als de ionosfeer tussen radiobron en ontvanger staat.
Zo hindert de ionosfeer radio-astronomen, omdat zij de voortplanting van radiogolven van de sterren naar de telescopen verstoort [2].
Ook bij verbindingen met communicatie- en navigatiesatellieten kan de ionosfeer roet in het eten gooien.
Daarentegen brengt de ionosfeer uitkomst bij radioverbindingen op aarde. Korte-golfzenders maken handig gebruik van het feit dat de ionosfeer radiogolven met een frequentie lager dan de plasmafrequentie (ongeveer 10 MHz) weerkaatst.
Zo kunnen wij in afgelegen oorden Radio Nederland Wereldomroep ontvangen, hoewel Hilversum ver onder de horizon ligt.

Over het globale gedrag van de ionosfeer is voldoende bekend, maar het zijn juist de verstoringen die astronomen en wereldomroepers hinderen. Het onderzoek in Eindhoven is erop gericht het gedrag van een bepaald type verstoring te doorgronden, namelijk de TID: de travelling ionospheric disturbance.
Een TID is een zich voortplantende oscillatie in de elektronendichtheid, die geassocieerd wordt met een zwaartegolf [3].
Een beter begrip van TID's begint met kennis van hun structuur, met een plaatje dus.
Tomografie van de ionosfeer stelt ons in staat dergelijke plaatjes te maken.

Tomografie

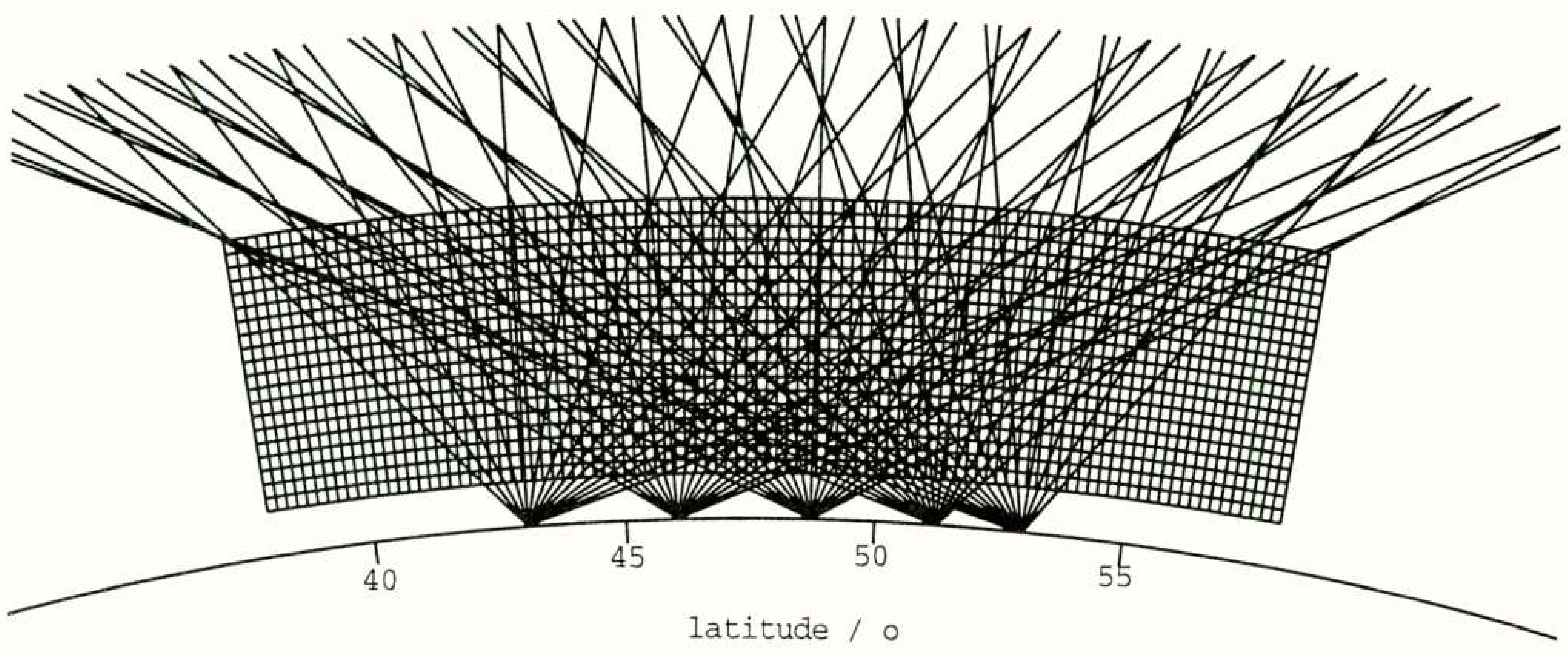
Tomografie is de techniek om een tweedimensionale verdeling te reconstrueren aan de hand van zijn lijnintegralen.
De bekendste toepassing is de medische CT (computerized tomography) scanner. Dit apparaat is eigenlijk een ring van rontgen-detectoren, waarbinnen een bron om de patient draait. De patient absorbeert een gedeelte van de straling en uiteindelijk meten de detectoren deze verzwakking.
Zo geeft elke meting de integraal van de absorptiecoefficient langs een straal. Na tomografische inversie levert dit een plaatje op van de absorptiecoefficient in een doorsnede van het lichaam.
Het Griekse woord $\tau o \mu \eta$ betekent dan ook snede.

In de geofysica wordt tomografie gebruikt voor bestudering van de oceanen en voor het afbeelden van het binnenste van de aarde [4]. Hierbij gebruikt men geen rontgenstralen maar geluidsgolven en seismische golven.
In het midden van de jaren tachtig ontstond het idee om met tomografie doorsneden van de ionosfeer te maken.
De techniek om lijnintegralen van de ionosferische elektronendichtheid te bepalen bestond al.
Deze techniek maakt gebruik van een navigatiesatelliet en een ontvanger.
De ontvanger bepaalt zijn positie door zijn relatieve snelheid ten opzichte van de satelliet te meten aan de hand van de Dopplerverschuiving van radiogolven uitgezonden door een radiobaken op de satelliet.
Omdat de baan van de satelliet bekend is, volgt de positie van de ontvanger.
De ionosferische refractie verstoort deze metingen.
Door op een tweede frequentie te meten en door gebruik te maken van het dispersieve karakter van de ionosfeer, kunnen zogenaamde geodetische ontvangers voor de ionosferische refractie corrigeren. Deze metingen stellen de onderzoeker ook in staat de integraal van de elektronendichtheid langs de gezichtslijn te bepalen.

De satellieten van het Amerikaanse Navy Navigation Satellite System (NNSS) lenen zich zeer goed voor de metingen. Deze satellieten bewegen in een cirkelvormige polaire baan op 1100 km hoogte. Bijgevolg valt het grondspoor van zo'n satelliet ongeveer samen met een meridiaan.
Om de metingen voor tomografie te kunnen gebruiken, plaatsen we een aantal ontvangers langs een lengtegraad, opdat ze ongeveer in een vlak liggen met een passerende satelliet.
De gezichtslijnen liggen ook in dit vlak en zo wordt dit het vlak van doorsnede, zie figuur 2.
In de figuur is direct te zien dat er een probleem is:
er zijn geen horizontale gezichtslijnen.
Een verzameling van zulke lijnen zou het hoogte-profiel weergeven.
Nu die ontbreken, is er een tekort aan informatie, namelijk over de verticale structuur. Dit is ook op een andere manier in te zien met behulp van figuur 2.
Stel dat de aarde plat is en dat de ionosfeer zuiver gelaagd is, de elektronendichtheid hangt dan alleen van de hoogte af.
Het verschuiven van die laag in de hoogte geeft geen verandering in de lijnintegralen zoals gemeten bij de ontvangers. In de metingen zit dus geen informatie over de hoogte van de laag.
Gelukkig blijft er dankzij de kromming van de aarde toch nog een beetje informatie over het hoogte-profiel behouden.

De tomografische inversie

Voordat we het experiment kunnen doen, moeten we weten hoe we uit de gemeten lijnintegralen de oorspronkelijke verdeling kunnen reconstrueren. De inversiemethoden van de medische CT scanner zijn voor de ionosfeer niet geschikt, omdat die methoden veronderstellen dat de lijnintegralen op zeer korte en regelmatige afstanden gemeten zijn.
Vanwege het beperkte aantal ontvangers en de ontbrekende horizontalen, voldoen wij niet aan die eis.
Wij zoeken onze toevlucht tot de discrete inverse theorie.
Hierin wordt de toestand van de ionosfeer gediscreti-



Figuur 2: De gezichtslijnen en het rooster van reconstructie.
Een op de zeven gezichtslijnen is getekend: zij gaan van de satelliet (boven) naar de ontvangers beneden.
De elektronendichtheid wordt geintegreerd langs de gezichtslijnen en deze metingen stellen ons in staat de elektronendichtheid in het rooster te reconstrueren. Het rooster loopt van 100 tot 700 km hoogte, hierbuiten is de elektronendichtheid zo laag dat ze verwaarloosd kan worden.

seerd, ofwel benaderd door een eindig aantal basisfuncties. De eenvoudigste manier is de pixel representatie. Dit vereenvoudigt het inverse probleem tot een stelsel van lineaire algebraische vergelijkingen, waarin de onbekenden staan voor de elektronendichtheid in een pixel, en een vergelijking overeenkomt met een lijnintegraal (een meting):

$$\mathbf{A}\,\mathbf{x} \approx \mathbf{d}\,.$$

Hier is **x** de vector met onbekende coefficienten, **d** de vector met de gemeten lijnintegralen en **A** is een reëele matrix, waarvan element (i,j) overeenkomt met de lengte van de doorsnijding van gezichtslijn j met pixel i.
Als gevolg van onder meer meet- en discretisatiefouten, is bovenstaand stelsel van vergelijkingen slechts in benadering correct, en mogelijk strijdig.

Met de discretisatie lijkt de oplossing nabij, want wat is eenvoudiger dan een stelsel lineaire algebraische vergelijkingen? Zelfs als het stelsel strijdig is, dan is er altijd nog de kleinste kwadraten oplossing.
Deze is gedefinieerd als die vector **x** die de discrepantie minimaliseert, waar de discrepantie gedefinieerd is als

$$\text{discrepantie} = \|\mathbf{A}\,\mathbf{x} - \mathbf{d}\|\,.$$

Met de Euclidische norm wordt deze vergelijking een kwadratische uitdrukking, vandaar de term kleinste kwadraten.
Het is eenvoudig een kleinste kwadraten oplossing uit te rekenen, maar het blijkt dat deze soms zeer gevoelig is voor kleine veranderingen in de metingen. Zozeer zelfs, dat de oplossing volledig onbruikbaar is. De instabiliteit is het gevolg van het feit dat er in de metingen te weinig informatie zit. In ons geval is dit het geval met de verticale structuur. De verticale structuur wordt zeer zwak afgebeeld in de metingen. De kleinste kwadraten methode versterkt deze zwakke afbeelding enorm om tot de oorspronkelijke structuur te komen. Meetfouten domineren de zwakke structuur echter volledig en worden door de kleinste kwadraten methode opgeblazen, zodat ze de oplossing domineren. Zo kan men zeggen dat het minimaliseren van de discrepantie de oplossing te nauw laat aansluiten bij de metingen, en dus ook bij de meetfouten. Dit veroorzaakt instabiliteit.
De instabiliteit is typerend voor inverse problemen met veel onbekenden en veel vergelijkingen. Men spreekt in dat geval van slecht gestelde problemen.

De verzameling methoden om de instabiliteit bij slecht gestelde problemen te beperken heet regularisatie.
Het ligt voor de hand hierbij het kleinste kwadraten principe te verlaten. Ook zal het nodig zijn de ontbrekende informatie te compenseren met voorkennis (a priori informatie).
Het kleinste kwadraten principe verlaten we door te stellen dat de oplossing moet voldoen aan

$$\|\mathbf{A}\mathbf{x} - \mathbf{d}\| = \mathbf{E}\;,$$

waar **E** de schatting van de lengte van de foutvector is.
Alle punten die hieraan voldoen zijn consistent met de metingen, omdat ze tot op de meetfout aan de metingen voldoen.
Er zijn echter oneindig veel van deze punten en met behulp van voorkennis moeten we dat punt uitkiezen,

dat a priori het meest waarschijnlijk is.

Het feit dat de elektronendichtheid nergens negatief kan zijn, vormt het eerste deel van de voorkennis.
Dit beperkt het aantal oplossingen, maar het is nog niet voldoende.
Ook weten we dat de ionosfeer in hoofdzaak een gladde en gelaagde structuur heeft en dat op kleine (100 km) en grote hoogte (700 km) de elektronendichtheid laag is. Deze informatie kunnen we in een functie O(x) stoppen, die groot is als x op gespannen voet staat met de voorkennis.
Door deze functie te minimaliseren kunnen we een oplossing forceren:

$$\min_{x \in S} O(x), \quad S = \{x \in R^n \mid E = \|Ax - d\| \wedge x \geq 0\}$$

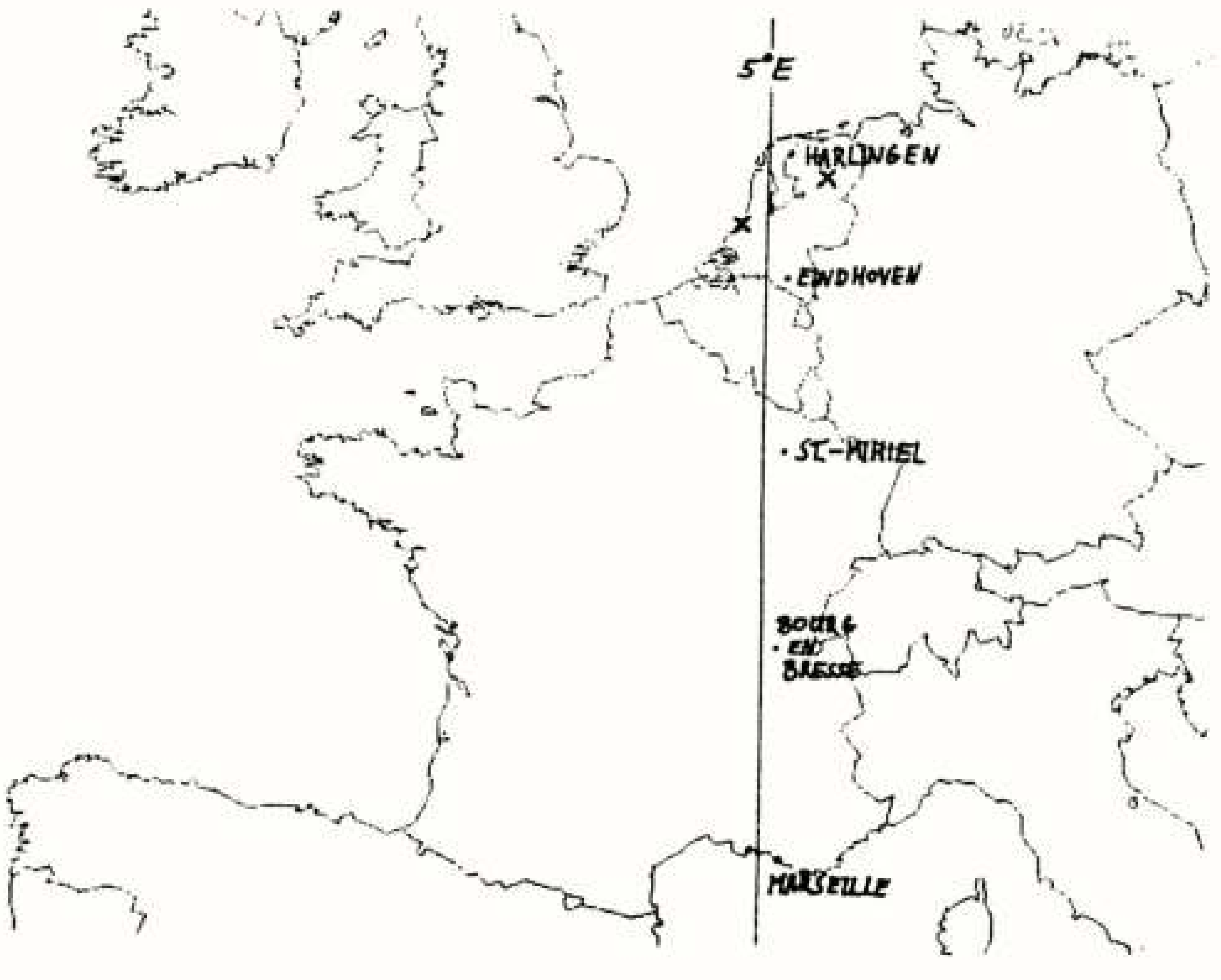
Deze oplossing heeft een eenvoudige interpretatie: van alle mogelijke elektronendichtheidsverdelingen die consistent zijn met de metingen en overal positief zijn, is het die verdeling, die het meest overeenstemt met de a priori kennis.

Het experiment

De NNSS satellieten zijn per passage ongeveer een kwartier boven de horizon.
De satellieten van het modernste navigatiesyteem, GPS (Global Positioning System), zijn per passage ongeveer vijf uur in zicht.
Dit maakt ze voor tomografie ongeschikt, omdat de ionosfeer in die periode sterk verandert. Met dit systeem gaat plaatsbepaling natuurlijk wel veel beter, en daarom hebben de nieuwe ontvangers de NNSS apparatuur naar het magazijn verbannen.
In Eindhoven konden we die wel gebruiken.
Zo hebben we vijf geodetische ontvangers van KLM Aerocarto in bruikleen en van de faculteit geodesie in Delft en van het KNMI elk ook nog een.

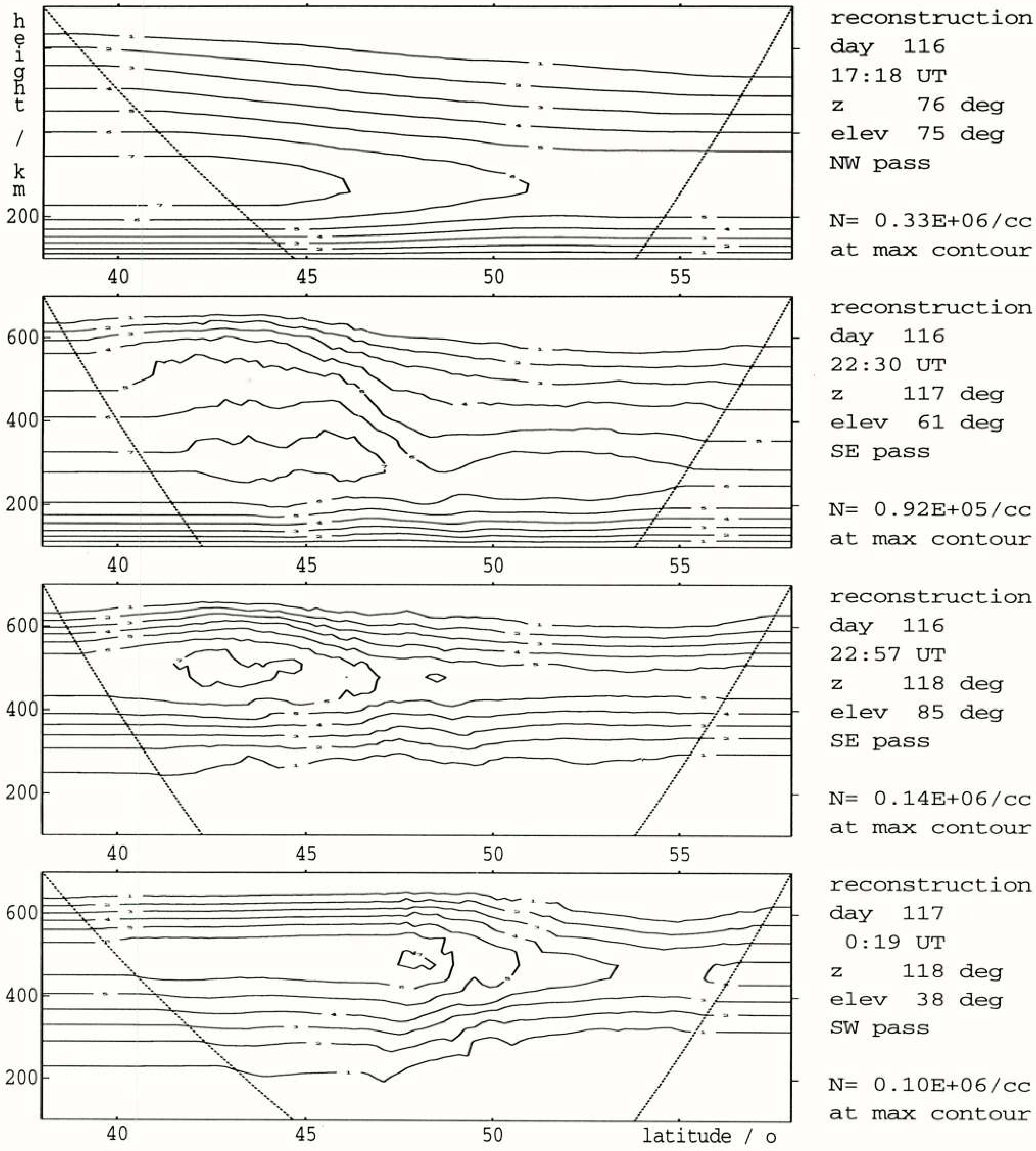
In het voorjaar van 1995 hebben we vijf van deze ontvangers geplaatst langs de meridiaan van Eindhoven (5 1/2˚o oosterlengte, zie kaartje). De meest noordelijke ontvanger kon terecht op de school voor de Rijn-, binnen- en kustvaart in Harlingen en de meest zuidelijke op de Faculte des Sciences in Marseille.
In Saint Mihiel (bij Verdun) stond er een op het dak van de lagere school en in Bourg en Bresse op de schouwburg.
Vanaf 21 maart 1995 hebben de ontvangers 45 dagen gefunctioneerd en daarna hielden ze er een voor een mee op.

Het experiment heeft 539 reconstructies opgeleverd, een gemiddelde van twaalf per dag.
Acht van die plaatjes staan in figuur 4. Het is een serie van een onrustige nacht, waar een verstoring van de gladde en gelaagde structuur zich ontwikkelt.
Een systematische interpretatie van alle gegevens toont aan dat de techniek werkt. Er is een redelijke

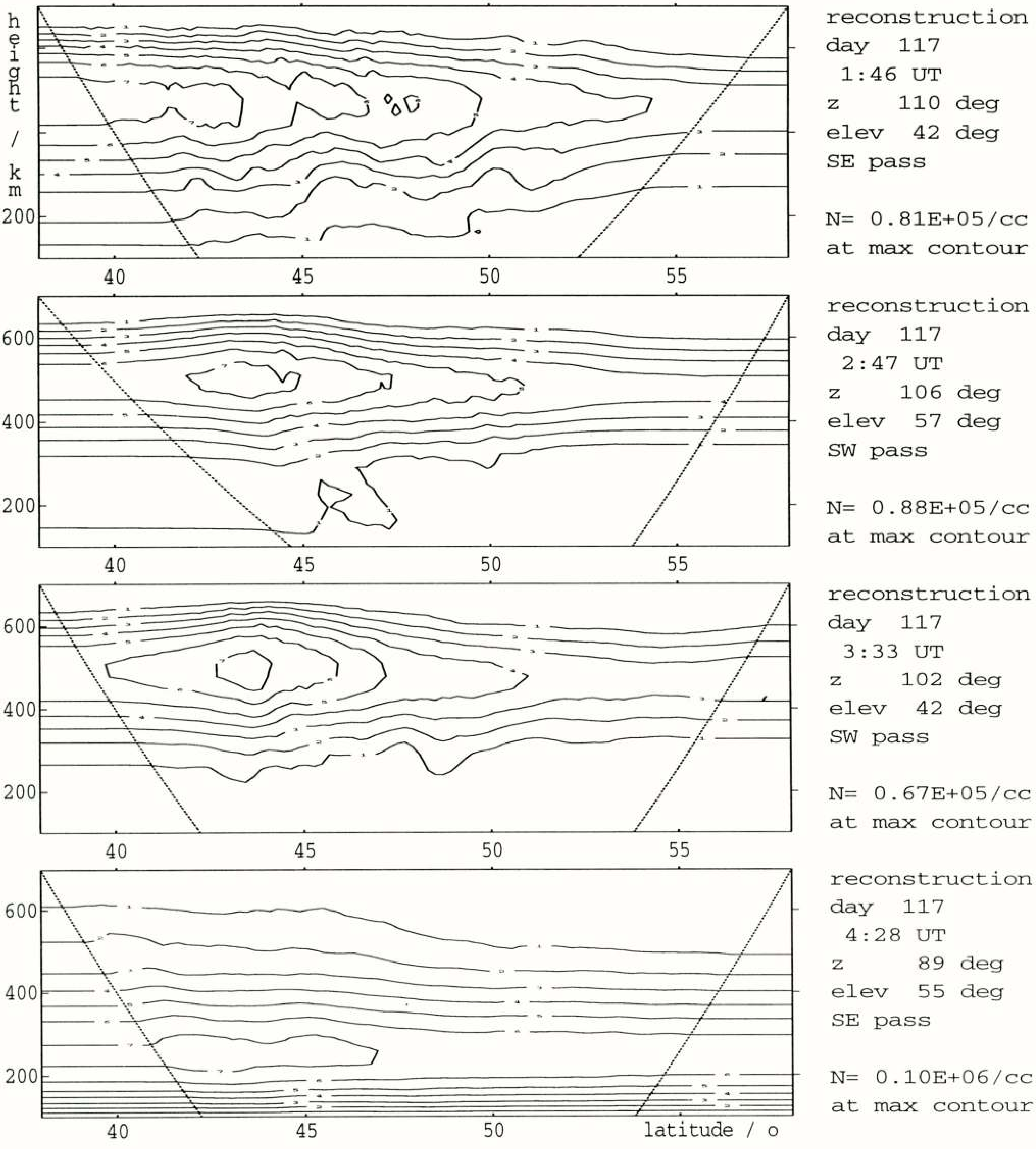


Figuur 3: Kaartje met de plaatsen waar de ontvangers stonden opgesteld.

overeenstemming met onafhankelijke metingen van de ionosferische elektronendichtheid boven Nederland, zoals die worden uitgevoerd door de Landmacht.
Ook blijkt dat de elektronendichtheid overdag groter is dan 's nachts, wat natuurlijk niet onverwacht is.
Interessanter is dat de laag van maximale elektronendichtheid 's nachts hoger ligt. Dit laatste is te verklaren uit het feit dat recombinatie op lagere hoogten sneller gaat, omdat er meer (neutrale) deeltjes zijn om de impulsbalans in de recombinatie-reacties kloppend te maken.
Het feit dat dit effect inderdaad wordt waargenomen suggereert dat we, ondanks de missende horizontale gezichtslijnen, toch uitspraken kunnen doen over het hoogte-profiel.


height / km
200
40
45
50
55
reconstruction
day 116
17:18 UT
z 76 deg
elev 75 deg
NW pass
N= 0.33E+06/cc
at max contour
600
400
200
reconstruction
day 116
22:30 UT
z 117 deg
elev 61 deg
SE pass
N= 0.92E+05/cc
at max contour
reconstruction
day 116
22:57 UT
z 118 deg
elev 85 deg
SE pass
N= 0.14E+06/cc
at max contour
reconstruction
day 117
0:19 UT
z 118 deg
elev 38 deg
SW pass
N= 0.10E+06/cc
at max contour
latitude / o

Figuur 4a



Figuur 4b

Figuur 4: Serie contourplots van een nachtelijke ionosfeer in beroering, 26/27 april 1995. Langs de horizontale as de geografische breedte en verticaal de hoogte.
De contouren verbinden punten van gelijke elektronendichtheid, de contour-schaal is lineair en de dichtheid op de hoogste contour staat rechts aangegeven.
De schuine stippellijnen komen overeen met de buitenste gezichtslijnen.
Buiten die lijnen vormen de reconstructies een gelaagde voortzetting, wat een gevolg is van de voorkennis. De serie is typisch voor een verstoorde nacht. Het begint met een rustige middag-ionosfeer. Na zonsondergang neemt de elektronendichtheid af, maar neemt de hoogte waar de maximale dichtheid wordt bereikt juist toe.
Onregelmatigheden worden zichtbaar die na zonsopgang weer verdwijnen.

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[3] Hennie Kelder en Titus Spoelstra,
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[4] Roel Snieder,
`Seismologie, de aarde doorgelicht',
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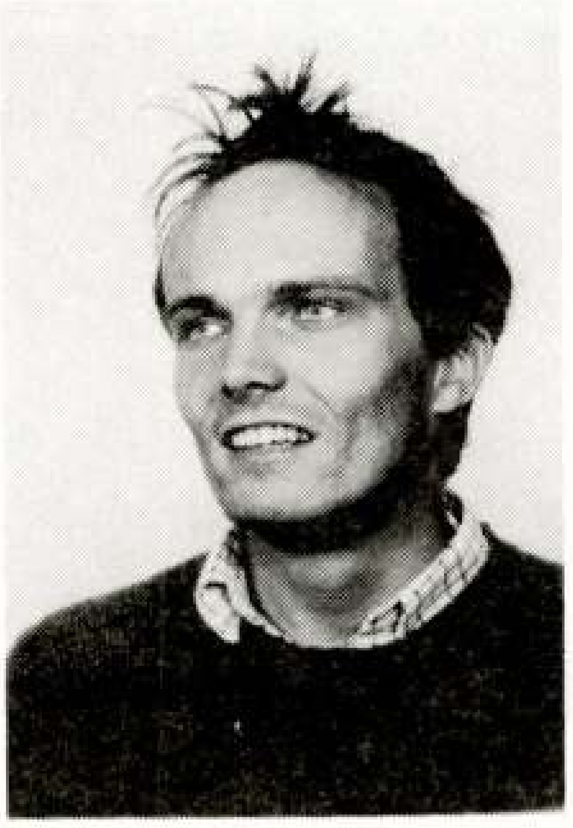

Gijs Fehmers (1966) studeerde sterrenkunde in Leiden. In 1992 verhuisde hij naar Eindhoven en verlegde zijn werkterrein van actieve sterrenstelsels naar de ionosfeer. Zo startte hij aan de TUE het door NWO gefinancierde promotieonderzoek waarover dit artikel verhaalt. Frans Sluiter en Leon Kamp waren daar zijn begeleiders, vanuit de Radio Sterrewacht Dwingeloo bijgestaan door Titus Spoelstra. Op 16 september 1996 is hij gepromoveerd. Inmiddels is hij werkzaam bij Shell Research in Rijswijk.

In een iets andere vorm is dit artikel eerder verschenen in het Nederlands Tijdschrift voor Natuurkunde: NTvN 62 (1996), 227-230.

De figuren van dit artikel zijn overgenomen uit het proefschrift getiteld: 'Tomography of the ionosphere'
T.U. Eindhoven
ISBN 90-386-0438-6

Voordracht gehouden tijdens de 450e werkvergadering

NEDERLANDS ELEKTRONICA- EN RADIOGENOOTSCHAP

UITNODIGING NERG WERKVERGADERING 450

Datum:	2 december 1996
Locatie:	N.B.C. "De Blokhoeve"
Adres:	Blokhoeve 1
Plaats:	Nieuwegein
Tijdstip:	18.00-22.00 uur

Onderwerp:

URSI

De International Radio Science Union of, volgens zijn Franse naam, Union Radio Scientifique International, is een van de oudste internationale wetenschappelijke organisaties op het gebied van het elektromagnetisme in de meeste brede zin.
De unie is georganiseerd in nationale commissies van de lidstaten en wetenschappelijke commissies op verschillende deelgebieden in een soort van matrix organisatie.
De wetenschappelijke commissies betreffen elektromagnetische meteorologie, velden en golven, signalen en systemen, elektronica en fotonica, elektromagnetische ruis en interferentie, golfvoortplanting en remote sensing, ionosferisch onderzoek, golven en plasma's, radio-astronomie en tenslotte elektromagnetisme in biologie en geneeskunde.
Driejaarlijks wordt er een algemene assemblee georganiseerd waar alle commissies, hetzij alleen hetzij in combinatie, bijdragen leveren in de vorm van symposia. De laatste assemblee was deze zomer in Rijssel (Frankrijk).
In deze werkvergadering zullen onderwerpen, besproken in de algemene assemblee, aan de orde komen.

PROGRAMMA

18.30 Ontvangst deelnemers met koffie / thee

19.00 Inleiding URSI
Prof.dr. F.W. Sluijter Technische Natuurkunde

19.25 Gepulste excitatie van gelaagde media
Prof.dr. A.G. Tijhuis (Faculteit Elektrotechniek TU Eindhoven)

20.05 Frequentiebeheer en radiosterrenkunde
Dr. T.A. Th. Spoelstra (Radiosterrenwacht Westerbork)

20.45 Tomografie van de ionosfeer
Dr. G.C. Fehmers (Shell Research Rijswijk)

21.25 Afsluiting met mogelijkheid na te praten in café

WILL RADIO ASTRONOMY SURVIVE?

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P.O.Box 2, 7990 AA Dwingeloo, The Netherlands

Abstract

Man-made interference of various kinds has an increasingly negative impact on radio astronomy. The key to the problem are the different characteristics of "passive" and "active" spectrum applications. By nature these are not compatible. Sophisticated hardware and software tools have to be developed to cope with interference effects in the data. In cases where this is not sufficient other solutions have to be found, like agreements between the different users involved. The pressure from commercial and industrial applications of radio is increasing exponentially. The paper discusses the relations involved, some legal aspects of agreements between users of different applications and the context for technical solutions. It also briefly indicates which organizations are involved in these processes.

---

1. Introduction

Radio astronomy suffers increasingly from man-made interference of various kinds. Several observatories are already in a position that research has to stop at a couple of frequencies. One of the main reasons is that the Radio Astronomy Service is till now the only exclusively passive service, which introduces a severe compatibility problem with active spectrum users: they often do not understand the nature of radio astronomy as a telecommunication service. The key of this problem lies in the characteristics of a passive service (see Sect.2). In general, passive spectrum use is practised by scientific research without any direct obvious commercial or industrial application. The pressure from commercial and industrial applications of radio is, however, increasing exponentially. This leads to the key question of whether passive services and scientific applications of radio will survive. To reduce the degradation of passive applications of radio, a variety of hardware and software tools is being developed. In many cases these are structurally insufficient. In general, one of the other options for the survival of passive services and scientific applications of radio is by agreements between e.g. passive and active users of the radio spectrum. These agreements are complementary to the frequency management work of the national administrations.

2. Active - Passive

A *passive service* is based on *reception only*: passive applications do not use transmitters nor are they able to control the whole system, the transmitter, the communication channel and the receiver. It can only control the receiver side of the "communication system". This is different from the *active services*, that do control the whole system, transmitters, channel and receiver. Therefore, the susceptibility of a passive service to interference from electromagnetic waves is larger than that of active services. The resulting differences are related to the factors that vary with sensitivity, signal to noise ratio, dynamic range, signal power and these differences make active and passive services very often more or less incompatible.

3. Radio Astronomy

Radio astronomy can exist only by virtue of the possibility of the detection of radio waves from celestial objects with a angular and frequency resolution and sensitivity sufficient to answer the scientific questions raised. The quality of the results depend very heavily on the quality of the experimental equipment (= radio telescope with its instrumentation) and the spectral purity of the measured signals. Radio astronomy as a physical science serves a better understanding of the physical world from the small events of daily life to the farthest depths of the universe.

Although the importance of science is beyond discussion, the scientific use of radio is under pressure. It should be noted that as soon as scientific applications of radio are restricted or reduced due to some decision or policy, this implies a direct and severe attack on scientific progress and the cultural heritage of humanity.

Passive frequency use is most vulnerable for pollution. This is particularly true for the radio signals relevant for scientific research. The science which is the best example of passive frequency use is radio astronomy. By its extremely sensitive sensing techniques it enables mankind to access physical conditions in the universe which are impossible to attain in a man-made laboratory. Radio astronomy does not give merely a description of the universe; it is providing tests for the laws of fundamental physics. The results of radio astronomical research have often opened new directions in other sciences and technology. This opening of new perspectives can only be achieved when certain frequency bands are 100% free of interference. These bands can not be selected at will, but are set by Nature itself [1]. A well-known example is the spectral line of neutral hydrogen at 21 cm wavelength (rest frequency 1420.4057 MHz).

4. Lat-Relations

Active and passive applications of radio are a fact of daily life. They even need each other and they prefer to co-exist on a non-interference basis: i.e. "living apart together" or LAT-relations.

However, more and more often, spectrum use by *active* services close to, or even within, the bands allocated to *passive* services does occur. This allocation is given in the Radio Regulations of the Radiocommunications Bureau of the International Telecommunication Union (ITU). Whether or not this is in agreement with the ITU-R Radio Regulations, it is detrimental to the quality of scientific radio use. This problems can occur in frequency bands with a shared allocation for active and passive services and also due to interference from out-of-band or spurious emission.

When the problems are related to sharing the same frequency band, two situations are possible:

[a] the services involved have a different status (the one primary and the other secondary). In this case, the secondary service has to comply with the criteria set by the primary service.

[b] both kinds of services have the same status. Then they both have to consider the restrictions set by the characteristics the other service.

Interference due to out-of-band and spurious emissions needs to be cured by the interfering transmitter. This is analogous to the "polluter pays" principle used in environmental pollution cases.

It is obvious that this LAT-relation will grow to harmonious maturity when the ITU-R Radio Regulations are obeyed.

5. International Law [3]

The ITU-R Radio Regulations are an international agreement with the status of international law. A treaty or contract will only obtain the status of international law when all partners taking part in this treaty should a priori obey [a] *the principle of good faith*, [b] *the principle not to do any harm to any partner involved in the treaty (now or later)*. The first principle implies for radio services that each respects the integrity of (the information given by) each of the others. The second principle implies that the criteria given by a service are considered by the others as inviolable.

At World Radio Conferences (WRCs) where these Radio Regulations are defined, the representatives of the different sovereign countries (which have the right to vote in these conferences) obey these principles.

The sovereignty of ITU member states implies that each sovereign countries is allowed to develop its own interpretation of the ITU-R Radio Regulations and define its own frequency allocation policy, as long as it does not conflict with the interests of neighbouring countries. This freedom is justified within the context of the ITU-R Radio Regulations.

The ITU convenes the World Radio Conferences because of its status as an international organization, i.e. belonging to the United Nations family.

In this context it is important to define which bodies are subjects in terms of international law and what is their status in this respect. This status turns out to be different for sovereign states, international organizations (like the UNO, ITU, European Union), multinational or transnational companies and the Vatican (having a different status because of the fact that it has both a political and a clerical status).

One of the important issues is whether a subject in international law is a recognized legal person. This is clear for states, international organizations (as far as recognized by non-member states) and the Vatican, but is very uncertain for multinational companies.

Subjects with a legal personality can make treaties, contracts, etc. in terms of international law. Multinational companies, however, have to operate under the national law of the country in which they operate. An international organization has the competence and authority given to it by the states forming this body. It has the legal status of a state in the sense that the states forming this body should follow its "policy" within the framework set by the member states: c.f. the role of the UNO, ITU, European Union.

Concerning harmonious LAT-relations between active and passive services, it turned out that the ITU-R Radio Regulations may not be comprehensive enough for all problems. And active users usually have more economic and technological power. This implies that a passive service needs to find ways to co-exist with an active service (preferably in close cooperation with the national administration of the state within which it will operate). Two solutions are possible: [a] an agreement, [b] a technical solution. The former needs to have a status similar to national or international law, while the latter can be implemented in various hardware or software techniques.

6. Agreements

Agreements between active and passive frequency users may be needed if the sharing conditions are not clear or cannot be met. In cases where active services operate in the same band as the Radio Astronomy Service very stringent precautions have to be taken to avoid harmful interference to the Radio Astronomy Service. This condition is due to the sensitivities achieved in radio astronomy, which are usually at least a factor of 108 larger than daily practice of active users [2].

Agreements concern global, regional and local problems. Global problems are e.g. space-borne transmissions. Regional topics are e.g. border crossing broadcast transmissions. Local problems can be very diverse. Global items are subject to international agreements such as the ITU-R Radio Regulations. When space operations have to be considered, the relevant document is the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies* of the United Nation Organization (OST). OST is *the* international law in this respect: the ITU-R Radio Regulations are an OST-related document.

The ITU-R Radio Regulations are the results of negotiations between legal personalities such as sovereign states and international organizations. Local agreements are subject to national law. Regional agreements are achieved between regional legal personalities, like the European Union.

The Inter-Union Commission on the Allocation of Frequencies for Radio Astronomy and Space Science (IUCAF) is concerned with *global* topics on behalf of scientific radio spectrum use. The Committee on Radio Astronomy Frequencies of the European Science Foundation (CRAF) deals with *regional* European items and bodies like the Committee on Radio Frequencies (CORF) of the US National Research Council with *local* problems (= problems which can be solved within the jurisdiction of one single country). If agreements are required, these bodies are the radio astronomy partners to negotiate with representatives of actives services.

Several kinds of agreements between active and passive services exist.

One kind of a local agreement is a "law" given by a national administration, such as the allocation of the frequency band 608-614 MHz to the Radio Astronomy Service in many countries in Europe prior to its use by an active service, i.e. broadcast. In this band the Radio Astronomy Service has a secondary allocation in Europe according to the ITU-R Radio Regulations, while a primary status has been allocated to the Broadcasting Service. Other agreements in which radio astronomy is involved have been established with the administration of the Russian Global Navigation Satellite System (GLONASS) and between the US National Radio Astronomy Observatory (NRAO) and the Motorola Company. The former one is a global agreement, while the latter one is local. Regional agreements have been achieved between e.g. the Conférence Européenne des Postes et Télécommunications (CEPT) and CRAF.

6.1. A global agreement: GLONASS and Radio Astronomy

In the case of GLONASS the following happened: The GLONASS transmissions interfered dramatically with radio astronomy observations within the band 1610.6-1613.8 MHz (for which the Radio Astronomy Service has a primary allocation). In November 1993, IUCAF reached an agreement with the GLONASS administration which included a plan for a step-by-step reduction in the interference levels to radio astronomy with the aim of reaching the ITU-R Recommendation RA769 level in 1999 by using filters and a different modulation scheme for the transmitted signal. At present the status is that no operational satellite has a carrier frequency inside the radio astronomy band. Secondly, the satellites which have been built and are being prepared for launch are being modified to avoid their spectra falling into the radio astronomy band. Thirdly, a new experimental modulator with an improved spectrum was built and tested, in part similar to what has been proposed by Ponsonby [4]. This modulator may be installed on future satellites.

We observe that IUCAF is a body of the International Council of Scientific Unions (ICSU) which has UNESCO as its umbrella organization. Although UNESCO is an international organization within the UNO, IUCAF is not a public actor in terms of international law. The GLONASS administration has, however, a public status in international law since it is state-owned/-controlled. The agreement between IUCAF and GLONASS, however, evolved into a model agreement that GLONASS could use for agreements with sovereign states, as has since happened so that now this agreement is valid world-wide.

In the process of preparing this IUCAF-GLONASS agreement and later during the technical developments by GLONASS it is noted that the principles of international law outlined in section 5 are obeyed.

6.2. A local agreement: the NRAO-Motorola MoU

In June 1994, The US National Radio Astronomy Observatory, NRAO, with observing sites at Green Bank and Socorro and operating the VLBA network signed an agreement with Motorola for the use of the band 1610.6-1613.8 MHz. This Memorandum of Understanding, MoU, contains operational and technical solutions for the noted problems. This MoU has been reached to facilitate Iridium Mobile Satellite Service operations. According to this MoU, radio astronomy will take all practicable steps to avoid peak traffic hours for the MSS operators. This implies, however, that *radio astronomy is forced to do its observations only in low-traffic hours*. In the design of the Iridium system no precautions against unwanted emissions and tools to protect radio astronomy observations have been implemented. From written documentation of Motorola it is clear that harmful interference to the Radio Astronomy Service by the Iridium system is be guaranteed (sic!).

NRAO is the only radio astronomy institute which has signed a MoU with Motorola. No other US observatory nor any observatory elsewhere has signed such an agreement. We should note that there is an agreement between Ohio State Observatory and Motorola: but this observatory is hardly operational and not interested in 1.6 GHz observations. The US observatory operating most of its time at 1.6 GHz is under strong political pressure to come to an agreement with Motorola. In Europe, no observatory will sign an MoU as NRAO did, since this does not consider the fact that an active spectrum user controls the operations of a radio observatory *protection*. CRAF has informed Motorola about the European decision. In addition CRAF participates in CEPT study groups to investigate the possibility of and conditions for sharing between active and passive spectrum use: in particular with respect to satellite operations.

In the case of Motorola the situation is very different from the GLONASS-IUCAF agreement: Motorola as a private US company (which it still is although it operates multinationally) reached an MoU with NRAO (a US organization). If necessary and if problems arise, these can only be solved subject to US national law (without any consequence for non-US organizations).

For an MoU of this kind two aspects need to be considered:

[a] The MSS operator can only operate under national law in the countries where it has a representation, since within international law it has no public status.

[b] An agreement between a multinational company and the Radio Astronomy Service is valid if the principles used to establish international law are obeyed. This implies that any such agreement should obey the OST and the ITU-R Radio Regulations as well.

In the case of the MoU between NRAO and Motorola it is clear that the principles mentioned in section 5 are violated, in particular the principle of not harming any partner involved in the treaty (now or later). Given the results, radio astronomy is degraded to less than a secondary status. In daily life we commonly call this kind of users of the spectrum "privateers" (just as occurs on the see).

7. Technical Solutions

The Motorola MoU with NRAO was linked to the installation of beacon transmitters at the observatory sites, i.e. of NRAO. This solution implies that when e.g. a Mobile Earth Station detects the beacon signal (i.e. when it enters a coordination zone around a radio observatory) its transmissions are inhibited. This solution is particularly relevant for the uplink signals.

The beacon "solution" contains several difficulties such as: which frequency band is used, what power will be transmitted, how is interference of the beacon signal to radio astronomy observations suppressed, how long will the MSS equipment radiate before it is inhibited (even tens of seconds can kill an astronomical project), is the action by MSS equipment adequate?

At present the beacon solution as recommended by several MSS operators has never been tested at any radio astronomy observatory, nor has any beacon ever been installed at a radio observatory. Furthermore, no test results of any beacon system for application at radio observatory sites are known, because it has never been installed or tested.

Another proposed way out of the problem is by blanking radio astronomy receivers as soon as an interfering signal is detected. This proposal might be applicable for both uplink and downlink signals. This blanking is one of the options for a radio observatory operating in a frequency band in which it has no primary allocation. Although blanking does remove interference from the radio astronomical observations, it implies a decision for planned and direct degradation of the radio astronomy observations. An agreement containing this option is *not* acceptable within frequency bands in which the Radio Astronomy Service and other scientific applications have a primary allocation. This evaluation depends on the characteristics of the research which is undertaken, i.e. integration times cannot be extended at will to alleviate this degradation due to the nature of the objects studied [1].

Before active radio users proposed their solutions, radio astronomers themselves were already developing hardware and software techniques to reduce the degradation of their observations by man-made interference [5]. These solutions depend very much on the kind of observations being done. Different techniques have to be developed for e.g. broad-band or continuum observations, narrow-band or spectral line observations, measurements with very high time resolution (as short as fractions of milliseconds), long integration times (as long as 12 hours). Furthermore, the solution might be different in case the allocation to the passive service is [a] primary exclusive, [b] primary and shared with active users or [c] with a lower status. When the allocation is secondary or lower, techniques have to be developed to do observations in a polluted environment. For this environment dynamic filtering methods are needed which depend on the modulation technique used by the active application.

Solutions for other scientific applications of radio will not be basically different from the situation for radio astronomy. One significant difference might be that the levels of harmful interference for radio astronomy are the most stringent and most difficult to comply with. But until now no practical technical solutions have been developed to avoid man-made interference incident on the antenna systems of scientific applications of radio. So far tools have been proposed and developed only to soften the suffering of science from the harm already done.

8. Space Pirates And Other ...

GLONASS and Iridium are not the only threats to radio astronomy. In Europe, various other threats exist. A partial list is:

- in frequency bands where passive frequency use has a primary exclusive allocation:

  * 25.55-25.67 MHz: broadcast causes harmful interference to radio astronomy observations in NanHay (France).

  * 1400-1427 MHz (protected with a footnote in the ITU-R Radio Regulations stating that all emissions are prohibited): in Germany, France and the Netherlands observations are threatened by communications among active spectrum users during the annual Tour de France operations.

  In Italy, radio astronomy observations suffer from strategic radar on Sicily. The military authorities promised to cure of this problem by December 1997.

- in frequency bands where passive frequency use with a primary allocation is shared with active services:
  * 322.0-328.6 MHz: observations in Germany, Italy, the Netherlands and Poland suffer harmful interference from transmissions by an unknown (= unregistered) satellite system operating at 328.25 MHz. The Dutch and German administrations put a lot of effort to find the operator of this system (also with help of the ITU) but so far they have not been not successful. This problem shows not only that partners in frequency land may cause harm to each other but also that the activity of pirates has been extended to outer space.
  * around 1.6 GHz: British, Dutch, German, French, Italian and Swedish radio observatories are threatened by interference from in-band, out-of-band and spurious emissions of space-borne systems operation at these frequencies.
  In Italy fixed links cause a specific local problem, for which solutions are sought in consultation between Italian radio astronomers, the Italian administration and CRAF. These local problems may have severe impact on the operations of a space-borne radio telescope which is to be launched on February 7th, 1997, and which will operated as part of the terrestrial networks for Very Long Baseline Interferometry (VLBI).
  * 10.6-10.7 GHz: German and Italian observatories suffer harmful interference from out-of-band emissions of satellite broadcasting from the ASTRA satellites.

In summary, just as occurs in daily life, radio astronomers suffer from pirates and privateers in the radio spectrum, while they like to live in proper LAT-relations with all spectrum users.

9. Spectrum Management

The LAT-relations mentioned above implie that the LAT partners need to have their well-defined spectrum "homes".

About 2% of the frequency bands of the total spectrum allocated in the ITU-Radio Regulations is allocated to passive radio use. This use consists of a mixture of different services, with different aims, for which different instruments are used and having different vulnerabilities to interference. Those scientific applications that intrinsically are sensitivity limited due to very a narrow bandwidth (if spectral line observations are made) or a very short integration time (e.g. in case of pulsar search) are especially vulnerable to interference.

It is noted that the pressure on the remaining 98% of the spectrum by active services is increasing at least exponentially. The solutions offered by active users until now to passive and scientific applications of radio turn out to be unrealistic.

This implies that more technical research has to be done before the vulnerable partner in the LAT-relation can continue to exist in its own part of the spectrum and before some kind of sharing agreement comes within reach. As long as this is not the case, solutions have to be found in the realm of administrative frequency management, subject to international and national law. Part of the administrative solution in the latter direction must be found in recognizing the inescapable needs of passive and scientific applications of radio and to declare a primary-exclusive status for an adequate set of frequency bands. For radio astronomy in addition to the band 1400-1427 MHz (or 21 cm band) the 18 cm OH bands (4 bands around 1.6 GHz) belong also to this category.

10. Conclusions

The radio spectrum is a unique natural phenomenon. Active and passive frequency use have always been closely associated. Active and passive frequency users find themselves more in competition than cooperation. Mutual cooperation and respect, however, is mandatory for the survival of vulnerable frequency use. This may result in agreements with the status of international law. The ITU and the administrations of the sovereign countries provide the frame within all this work can be done. It may, however, be that the technical development does less sufficient fit the regulatory process than was the situation in the past decades. If this is so, new regulatory methods and tools have to be developed. But vital for harmonious LAT-relations is that the regulatory activity remains an activity of administrations and does not become a process controlled and managed by interest groups.

On the other hand the technical progress in both kinds of services is of mutual interest and benefit. It may help to find ways to escape the more and more pressing interference problems.

For the active services themselves, it is obvious that as long as they cannot solve their problems in 98% of the spectrum, they cannot do this in 100% of the spectrum. Therefore, passive services and scientific applications of radio, radio astronomy in particular, will survive as long as the principles of good faith and not to do any harm to any partner involved (now or later) are obeyed.

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NEDERLANDS ELEKTRONICA- EN RADIOGENOOTSCHAP

UITNODIGING NERG WERKVERGADERING 452

Datum:	15 januari 1997
Locatie:	Philips research Laboratories
Adres:	Prof. Holstlaan 4
Plaats:	Waalre
Tijdstip:	12.45 - 16.00 uur

Onderwerp:

Digital Signal Processing

PROGRAMMA

12.45 Ontvangst, koffie

13.15 Aankondiging en uitreiking IEEE Awards

13.45 "Coding techniques and signal processing for digital recorder products"
Prof.dr.ir. Kees A. Schouhamer Immink
(Philips Research)

14.30 Koffie- en theepauze

15.00 "Data conversion", the key to digital signal processing of analog signals
Prof. Dr.ir. Rudy J. van de Plassche
(Philips Research)

15.45 Aankondiging samenwerking IEEE - NERG

16.00 Gelegenheid tot napraten met een borrel.
Aangeboden door IEEE -Benelux Sectie

Namens het NERG / IEEE,
Prof. Dr. J.B. Peek (past chairman IEEE)
Ir. W. van der Bijl (programma manager NERG)

CHANNEL CODES FOR DIGITAL RECORDERS

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Abstract

The article gives a survey of modulation codes used in storage devices such as Compact Discs, DVD, hard discs drives, and video recorders.

1. Introduction

A code is a set of rules for replacing a given source sequence, with another sequence which is recorded or transmitted. The aim of this transformation is to improve both the reliability and efficiency of the channel. The reliability is commonly expressed in terms of the probability of receiving the wrong information that differs from what originally was transmitted. The quantity efficiency is related to the amount of information that can be stored given the physical limitations of the recorder. The coding problem is partitioned into two main categories: *source* and *channel* coding. Source coding is, roughly speaking, a technique to reduce the source symbol rate by removing the redundancy in the source signal. In recorder systems, channel encoding is commonly accomplished in two successive steps: (a) error-correction code and (b) recording (or modulation) code. The output generated by the recording code is stored on the storage medium in the form of binary physical quantities, for example pits and lands, or positive and negative magnetizations. During read-out the recorder reconstitutes the input sequences as accurately as possible. Error-correction codes make it possible for the receiver to detect and/or correct the majority of the errors that may occur in the received message.

The arrangement called *recording code* on which this chapter will concentrate, converts the inputstream to a signal suitable for the specific physical requirements. For example in optical recording, information is recorded in the form of pits, and the absence of pits, called lands. If source 'ones' would be written as pits and source 'zeros' as lands, than a long sequence of source 'zeros' would mean that, as no pits are written, the track would be absent for some undefined time. This may pose problems with the tracking during reading, and track loss could be the result. This serious difficulty can be circumvented by using a recording code, which transforms the source sequence into a sequence, where such long strings of 'zeros' cannot occur.

Many kinds of recording codes are found in the recording area. In this chapter, we will deal with three types of recording codes, namely:

* *Runlength-limited sequences*. Recording codes based on runlength (RLL) sequences have found widespread application in optical and magnetic disc recording practice. RLL sequences are characterized by two parameters, $(d+1)$ and $(k+1)$, which represent the minimum and maximum runlength of the sequence, respectively. The maximum runlength constraint guarantees a clock pulse within some specified time, which is needed for the clock regeneration at the receiver. The maximum runlength constraint is dictated to increase the storage capacity.
* *Dc- constraint codes*. Another noteworthy family of codes found in recording systems is the group of *spectral null* codes, that is, codes that have vanishing spectral density at specific frequencies. Among these, codes with a spectral null at the zero frequency have predominated in applications. We refer to these as *dc-free* or *dc-balanced* codes.
* *Generation of pilot tracking tones*. Codes can also be used to tailor the signal to other spectral properties. To illustrate this idea, we shall discuss how recording codes have been created to produce low-frequency pilot tracking tones that can be exploited for servo tracking purposes.

A list of recording codes used in consumer electronics storage products is shown in Table 1. We start with an outline of runlength-limited codes followed by a description of dc-free and pilot tracking tones. A comprehensive discussion of recording codes can be found in [2,3].

TABLE I

Survey of recording codes and its application area

Device	*Code*	*Type*
Compact Disc	EFM	RLL, dc-free
DVD	EFMPlus	RLL, dc-free
R-DAT	8-10	dc-free
floppy and hard disk	(2,7) or (1,7)	RLL
DCC	ETM	dc-free
Scoopman [1]	LDM-2	RLL, dc-free
DVC	$24 \rightarrow 25$	pilot tones

2. Runlength-limited sequences

Codes based on runlength-limited sequences are the state of the art corner stone of current disc recorders whether their nature is magnetic or optical. The length of time (usually expressed in channel bits) between consecutive transitions is known as the *runlength*. Runlength-limited (RLL) sequences are characterized by two parameters, $(d+1)$ and $(k+1)$, which stipulate the minimum and maximum runlength, respectively, that may occur in the sequence. The parameter d controls the highest transition frequency and thus has a bearing on intersymbol interference when the sequence is transmitted over a band-with-limited channel. In the transmission of binary data it is generally desirable that the received signal is self-synchronizing or self-clocking. Timing is commonly recovered with a phase-locked loop which adjusts the phase of the detection instant according to observed transitions of the received waveform. The maximum runlength parameter k ensures adequate frequency of transitions for synchronisation of the read clock. The grounds on which the parameters d and k are chosen, in turn, depend on various factors such as the channel response, the desired data rate (or information density) and the jitter and noise characteristics. The rate 1/2, $(d = 2, k = 7)$ or rate 2/3, $(d = 1, k = 7)$ codes are applied in rigid or floppy disk drives, and the EFM code (rate = 8/17, $d = 2, k = 10$) is employed, in the Compact Disk and its derivatives CD ROM, CD-I, and the Mini Disk.

In order to describe RLL codes, it is convenient to introduce another constrained sequence, which is closely related to an RLL sequence.

Definition: A *dk*-limited binary sequence, in short, *(dk)* sequence, satisfies simultaneously the following two conditions:

1. d constraint - two logical 'ones' are separated by a run of consecutive 'zeros' of length at least d.

2. k constraint - any run of consecutive 'zeros' is of length at most k.

In general, a *(dk)* sequence is not employed in optical or magnetic recording without a simple coding step. A *(dk)* sequence is converted to a runlength-limited channel sequence in the following way. Let the channel signals be represented by a bipolar sequence $\{y_i\}$, $y_i \in \{-1,1\}$.
The channel signals represent the positive or negative magnetization of the recording medium, or pits or lands when dealing with optical recording. The logical 'ones' in the *(dk)* sequence indicate the position of a transition

$1 \rightarrow -1$ or $-1 \rightarrow 1$ of the corresponding runlength-limited sequence. The *(dk)* sequence.

0 1 0 0 0 1 0 0 1 0 0 0 1 1 0 1 . ..

would be converted to the RLL channel sequence:

1 -1 -1 -1 -1 1 1 1 -1 -1 -1 -1 1 -1 1 ...

The mapping of the waveform by this coding step is known as *precoding*. It can readily be verified that the minimum and maximum distance between consecutive transitions of the RLL sequence derived from a *(dk)* sequence is $d+1$ and $k+1$ symbols, respectively, or in other words, the the RLL sequence has the virtue that at least $d+1$ and at most $k+1$ consecutive like symbols occur. Table II gives some parameters of RLL codes that have found practical application.

A. EFM code

EFM, used in the Compact Disk, is both a dc-free and runlength-limited code. There are two reasons why EFM suppresses the low-frequency components. In the first place, the servo systems for the track following and focusing are controlled by low-frequency signals, so that low-frequency components of the information signal could interfere with the servo-systems. In the Compact Disk system the frequency range from 20 kHz to 1.5 MHz is used for information transmission, whereas the servo systems operate on signals in the range from 0 to 20 kHz. The second reason is that low-frequency disturbances in the retrieved signal resulting from fingerprints or dirt on the disc can be filtered out without distorting the data itself. The (high-pass) filter should be chosen to pass the signal and to reject the low-frequency noise. It cannot simultaneously do both completely.
Under EFM rules the data bits are translated eight at a time into fourteen channel bits, with minimum runlength parameter $d = 2$ and a maximum runlength parameter $k = 10$ channel bits (this means at least 2 and at most 10 successive 'zeros' between successive 'ones'.) Part of the EFM coding table is presented in Table III, which shows the decimal representation of the 8-bit source word (left column) and its 14-bit channel representation. It should be appreciated that the codewords are described in NRZI (non return-to zero inverted) notation, which means that a

TABLE II
Various codes with runlength parameters d and k

d	k	R	Name	
0	1	1/2	Bi-phase	(dc-free)
1	3	1/2	MFM,Miller	
2	7	1/2	(2,7)	
1	7	2/3	(1,7)	
1	4	1/2	LDM-2	(dc-free
2	10	8/17	EFM	(dc-free

TABLE III
Part of the EFM coding table

Data	*Code*	*Data*	*Code*
100	01000100100010	112	10010010000010
101	00000000100010	113	00100000100010
104	01001001000010	116	00010001000010
105	10000001000010	117	00100001000010
106	10010001000010	118	01001000000010
107	10001001000010	119	00001001001000
108	01000001000010	120	10010000000010
109	00000001000010	121	10001000000010
102	01000000100010	114	01000010000010
103	00100100100010	115	00000010000010
110	00010001000010	122	01000000000010
111	00100001000010	123	00001000000010

'one' represents a transition of either positive or negative polarity, and a 'zero' represents the absence of a transition. As a result, the lengths of the pits and lands recorded lie between three and eleven unity lenghts. It is easily seen that at least two bits, called *merging bits*, are required to ensure that the runlength conditions continue to be satisfied when the codewords are cascaded. If the runlength is in danger of becoming too short, we choose 'zeros' for the merging bits; if it is too long we choose a 'one' for one of them. If we do this, we still retain a large measure of freedom in the choice of the merging bits. This freedom is used for minimizing the low-frequency content of the signal. In itself, *two* merging bits would be sufficient for continuing to satisfy the runlength conditions (see also later). A third merging bit is necessary, however, to give sufficient freedom for effective suppression of low-frequency content, even though it entails a loss of 6 % of the information density on the disc (see also next section). The merging bits contain no information, and they are removed from the bit stream in the demodulator. Figure 1 illustrates, finally, how the merging bits are determined.
Our measure of the low-frequency content is the *running digital sum* (RDS); this is the difference between the totals of pit and land lengths accumulated from the beginning of the disc.

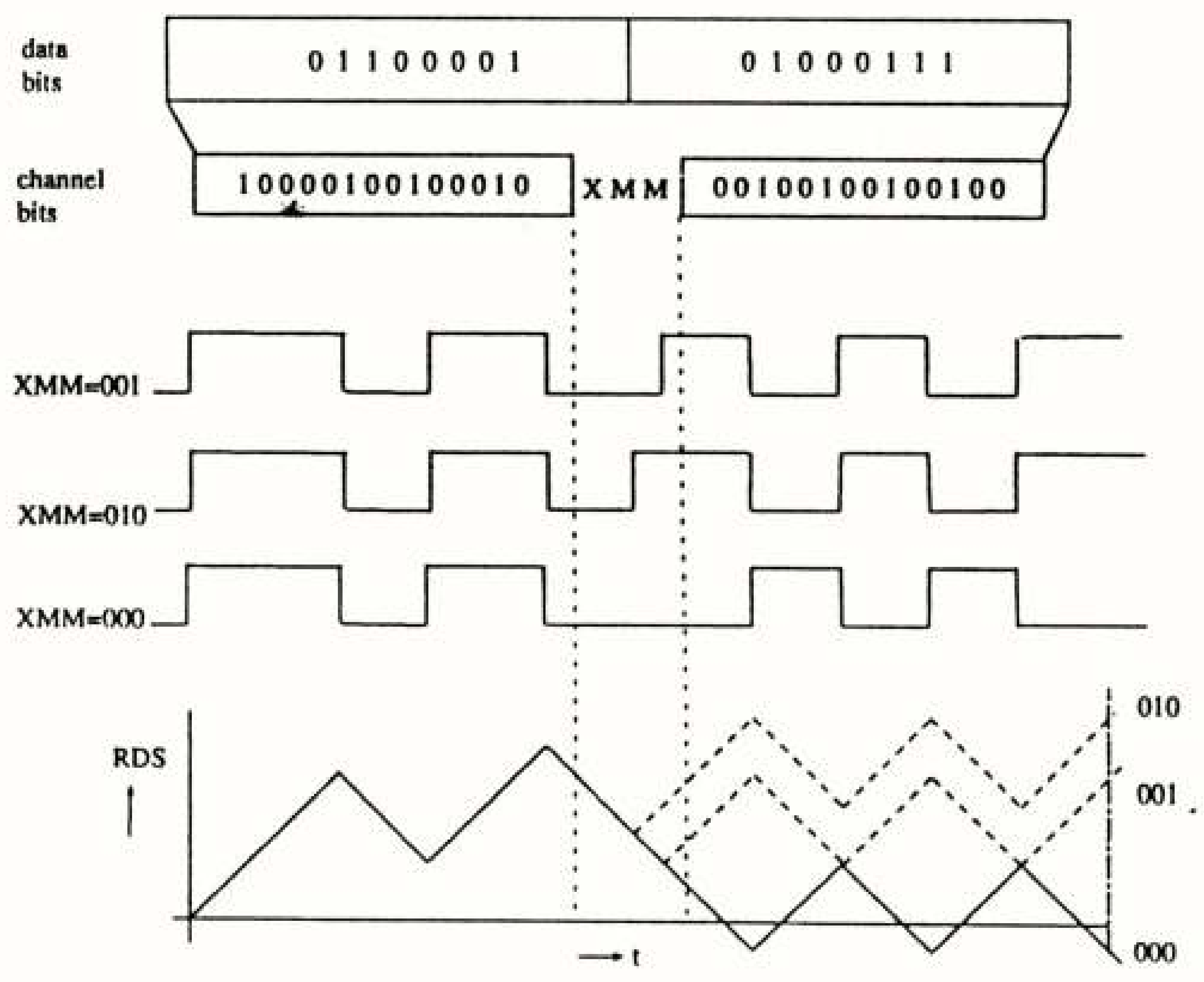

Figure 1. Strategy for minimising the running digital sum RDS).
Eight user bits are translated into 14 channel bits. The 14 bits are merged by means of 3 mergig bits in such a way that the runlength conditions continue to be satisfied. The proviso is that there should be at least 2 'zeros' between 'ones' requires a 'zero' at the first merging bit position. In this case there are thus three alternatives for the merging bits: '000', '010', and '001'. The encoder chooses the alternative that gives the lowest absolute value of the RDS at the end of a new codeword, i.e. '000' in this case.

At the top, two 8bit data words are shown From the $d = 2$ rule, the first of the merging bits in this case must be a 'zero'. This position is marked 'x'. In the following positions the choice is free. These are marked 'm'. The three possible choices 'xmm' = '000', '010' and '001' would give rise to the patterns of pits as illustrated and to the indicated waveform of the RDS, on the assumption that the RDS was equal to '0' at the beginning. The system now opts for the merging combination that makes the RDS at the end of the second codeword as close to zero as possible, i.e. '000' in this case. If the initial value had been -3, the merging combination '001' would have been chosen. The Power Spectral Density (PDS) function of conventional EFM has been obtained by computer simulation. Results are plotted in figure 2. Both axes are normalised for fixed user bit rate f_b.

B. EFM Plus

An extension of the Compact Disc family, the Digital Versatile Disc (DVD), is a proposal for a new optical recording medium with a storage capacity seven times higher than the conventional Compact Disc.
The major part of the capacity increase is achieved by the use of optics, shorter wavelength and lager numerical aperture, that reduces the spot diameter by a factor 1.5.
The track formed by the recorded pits and lands as well as

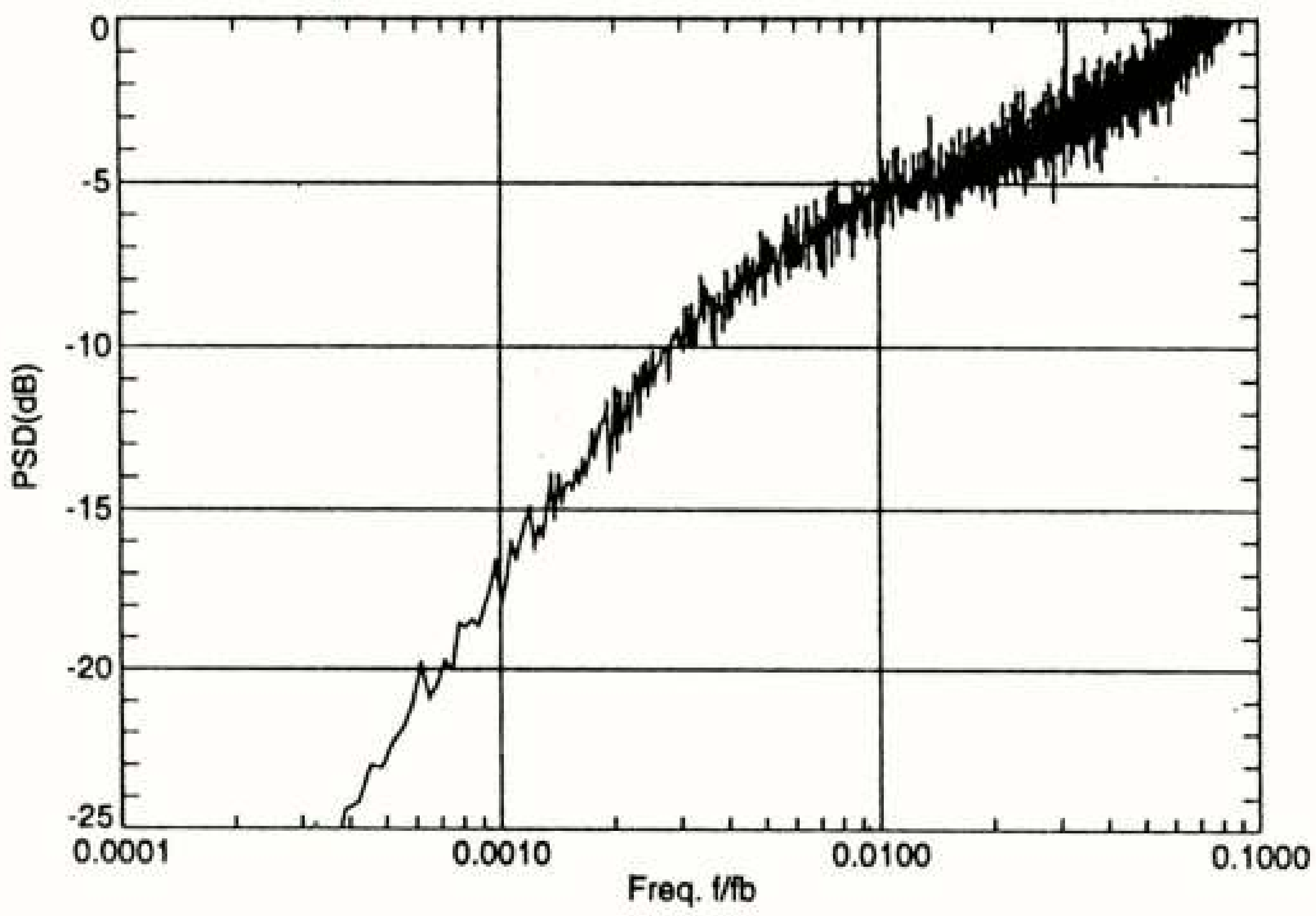

Figure 2 Spectrum of conventional EFM.

the track pitch can be reduced by the same factor. The storage capacity is further increased by a complete redesign of the logical format of the disc including a more powerful error correction and recording code (EFM Plus) [4]. The rate of EFM Plus is 8:16 and is therefore capable of recording 6 % more user information than is possible with EFM whose rate is 8:17. The principle of operation of the encoder can be represented by a finite-state sequential machine with an 8-bit input, a 16-bit output, and four states which are functions of the (discrete) time. We say that the states are connected by edges, and the edges, in turn, are labelled with tags called *words*. A word in our context is a 16-bit sequence that obeys the prescribed (d = 2, k = 10) constraints. Each of the four states is characterized by the type of words that enter, or leave, the given state. The states and words sets characterized as follows.

* Words entering State 1 end with {0,1} trailing 'zero' ;
* Words entering State 2 and 3 end with {2,...,5} trailing 'zeros';
* Words entering State 4 end with {6,...,9} trailing 'zeros'.

The words leaving the states are chosen in such a way that the concatenation of words entering a state and those leaving that state obey the (d = 2, k = 10) channel constraints. Words emerging from State 2 and 3 comply with the above runlength constraints, but they also comply with other conditions. Words leaving State 2 have been selected such that the first (msb) bit, x_1 and the thirteenth bit, x_{13} are both equal 'zero'.

In a similar fashion, words leaving State 3 are characterized by the fact that the 2-tuple x_1x_{13} does not equal '00'. The attributes of the four states just defined guarantee that any walk through the graph, stepping from state to state, produces a (d =2, k =10) - constrained sequence by reading the words tagged to the edges that connect the states. We find that from each of the states at least 351 words are leaving. An encoder is constructed by assigning a source word to each of the 351 edges that leave each state. Excess edges are removed. Also edges are removed that could generate the unique synchronization pattern. As a result, each edge in the graph has now two labels, namely a 16-bit word and a source word numbered from 0 to 344. Given the source word and the encoder state, the encoder will transmit the word tagged to the same edge as the source word at hand. The encoder requires accommodation for only 256 source words. The surplus 344 - 256 = 88, words will be used for controlling the lowfrequency power (see later).

The encoder is defined in terms of three sets: the inputs, the outputs and the states, and two logical functions: the *output function* and the *next state function*. The specific codeword, denoted by x_t, transmitted by the encoder, at instant t is, of course, a function of the source word b_t that enters the encoder, but depend further on the particular state, s_t, of the encoder. The output function $h(.)$ and the next state function $g(.)$ can be written as:

$$x_t = h\,(b_t, s_t)$$

$$s_{t+1} = g\,(b_t, st).$$

Both the output function $h(.)$ and the next-state function g(.) are described by four lists with 351 entries. A part of the output function and the next-state function is listed in Table IV. Table IV has an entry column that describes the source (input) word i by an integer between '0' and '255'. The table also shows h(i,s) the 16-bit output to a particular input i when the encoder is in one of the four states s. The words are written in NRZI notation. The 3rd, 5th, 7th, and 9th columns show the next state functions g(i,s). Let the encoder graph be initialized at State 1 and let further the the source sequence be '8', '3', '4'. The response to input '8', while being in State 1, equals h (8,1) = (see table IV) , '0010000010010000'. The new state becomes g (8,1) = 3.

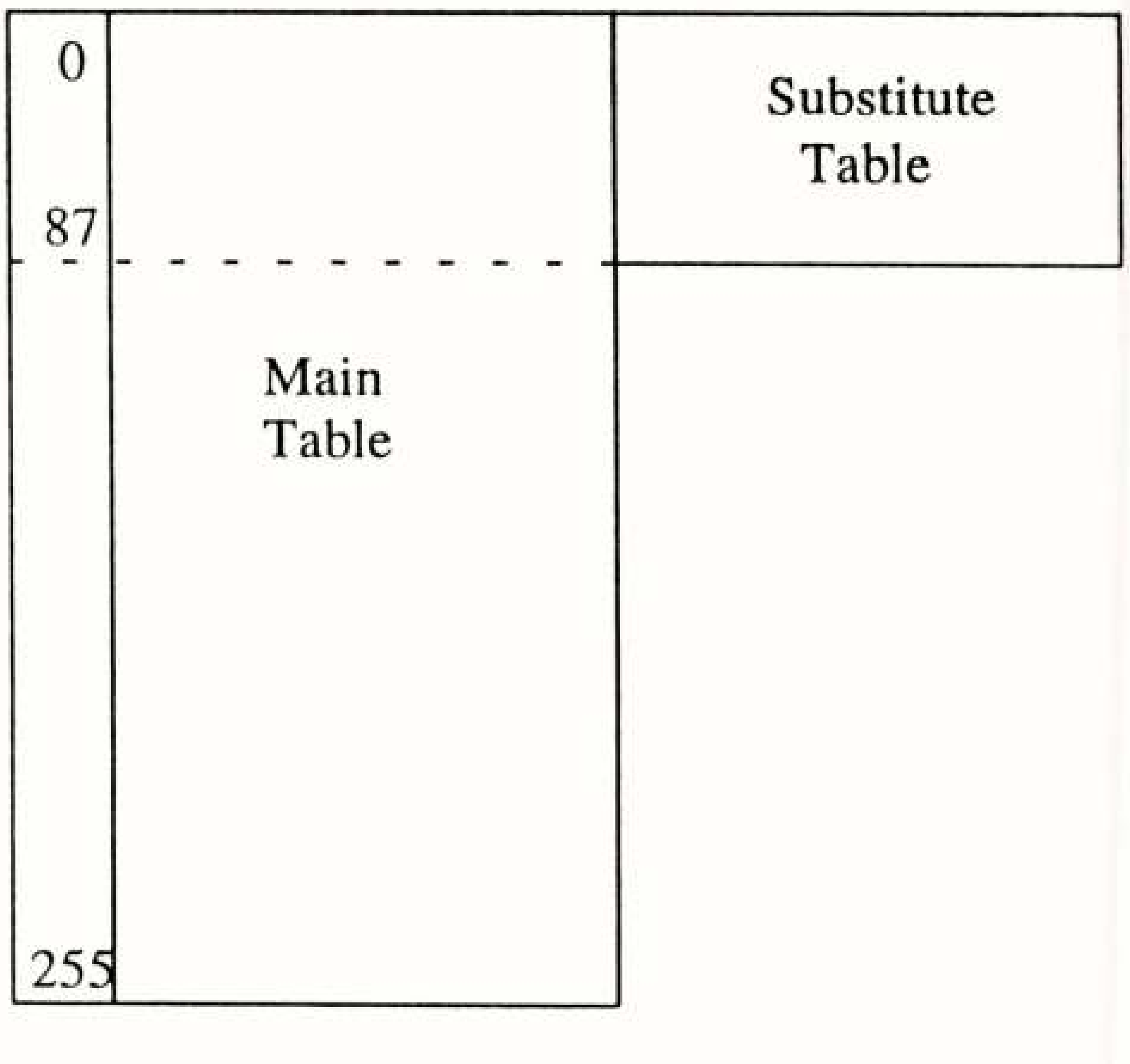

Figure 3 Blockdiagram of EFM Plus encoder

As a result, the response to input '3', while now being in State 3, is '0010000001001000'. In the next clock cycle, the encoder state becomes g(3,3) = 2. From State 2 with

TABLE IV
Part of the EFMPlus coding table

i	$h(i,1), g(i,1)$	$h(i,2), g(i,2)$	$h(i,3), g(i,3)$	$h(i,4), g(i,4)$
0	0010000000001001, 1	0100000100100000, 2	0010000000001001, 1	0100000100100000, 2
1	0010000000010010, 1	0010000000010010, 1	1000000100100000, 3	1000000100100000, 3
2	0010000100100000, 2	0010000100100000, 2	1000000000010010, 1	1000000000010010, 1
3	0010000001001000, 2	0100010010000000, 4	0010000001001000, 2	0100010010000000, 4
4	0010000010010000, 2	0010000010010000, 2	1000000100100000, 2	1000000100100000, 2
5	0010000000100100, 2	0010000000100100, 2	1001001000000000, 4	1001001000000000, 4
6	0010000000100100, 3	0010000000100100, 3	1000100100000000, 4	1000100100000000, 4
7	0010000001001000, 3	0100000000010010, 1	0010000001001000, 3	0100000000010010, 1
8	0010000010010000, 3	0010000010010000, 3	1000010010000000, 4	1000010010000000, 4

the input equal to '4' we find from the table that the corresponding output is
$h(4,2)$ = '0010000010010000'.
The encoder defined above can freely accommodate 344 source words. As we only need accommodation for 256 source words, the surplus of 88 words can be used for minimizing the power at low frequencies, in short, the dc-control.
The suppression of low-frequency components or dc-control is done in the same vein as in the EFM code, namely by controlling the running digital sum (RDS). The surplus words are used as an alternative channel representation of the source words 0,....,87. The full encoder is described by two tables called *main* and *substitute* table, respectively (see figure 3). The main table describes an encoder table of 256 inputs. The substitute table shows a similar table of 88 words which act as alternative representation of the source words 0,....,87 of the main table.
The source words 0,....,87 can thus be represented by the designated entries of the main table or alternatively by the entries of the substitute table. The power spectral density of the new code has been computed by a computer program which simulated the encoder algorithm. Results are plotted in figure 4. Note that the PSD is only 1-2 dB worse than that of conventional EFM.

3. Dc-free codes

Binary sequences with spectral nulls at zero frequency have found widespread application in optical and magnetic recording systems. *Dc-balanced* codes, as they are also called, have a long history and their application is certainly non confined to recording practice. Since the early days of digital communication over cable, dc-balanced codes have been employed to counter the effects of low-frequency cutoff due to coupling components, isolating transformers, etc. Suppression of the lowfrequency components is achieved by restricting the unbalance of the transmitted positive and negative pulses. In optical recording, as explained, dc-balanced codes are employed to circumvent or reduce interaction between the data written on the disc and the servo systems that follow the track. In the next section, we will show how dc - balanced codes are constructed.

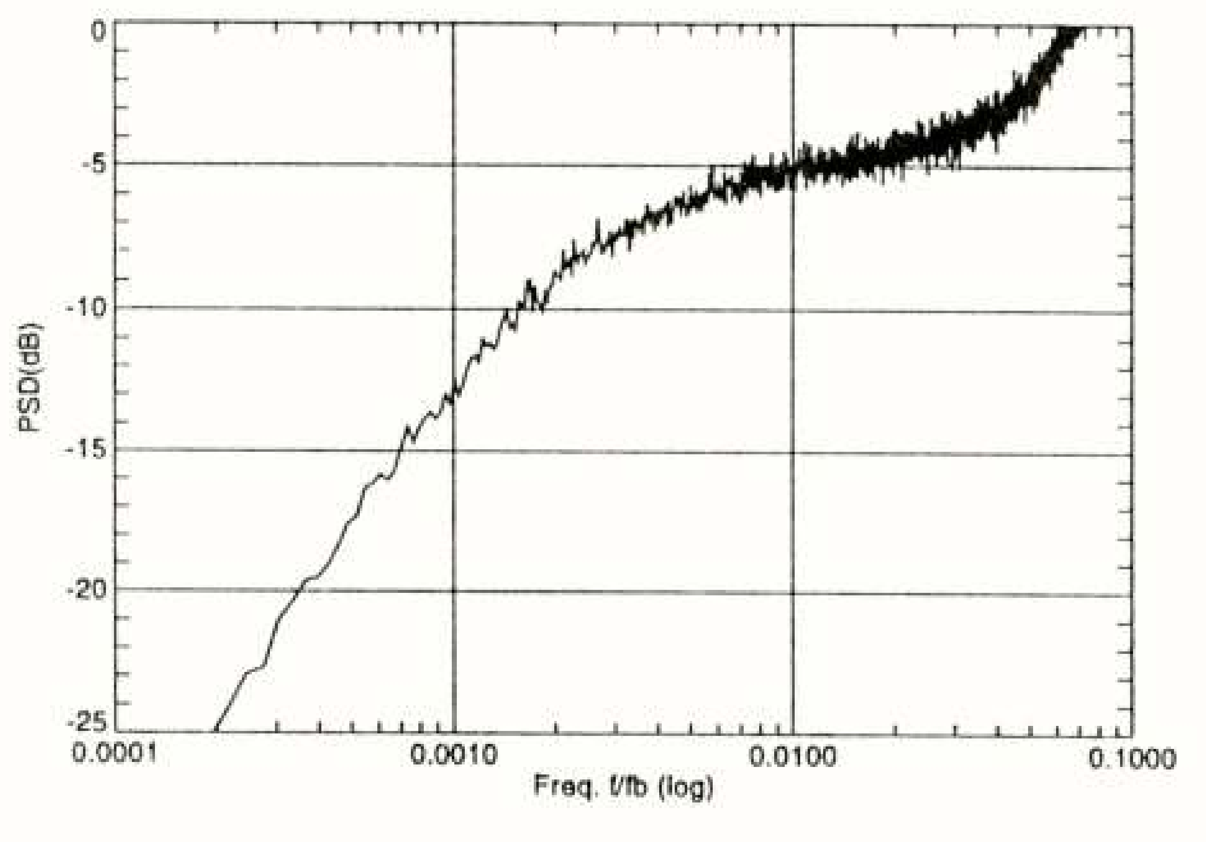

Figure 4. Spectrum of EFM Plus.

A. Properties of Dc-balanced Sequences

The running digital sum of a sequence, in short, RDS plays a significant role in the analysis and synthesis of codes whose spectrum vanishes at the lowfrequency end. Let

$$\{x_i\} = \{\ldots, x_1, x_0, \ldots, x_i, \ldots\} \; x_i \in \{-1, 1\}$$

be a binary sequence. The (running) digital sum z_i is defined as

$$z_i = \sum_{j=-\infty}^{i} x_j = z_{i-1} + x_i \qquad (1)$$

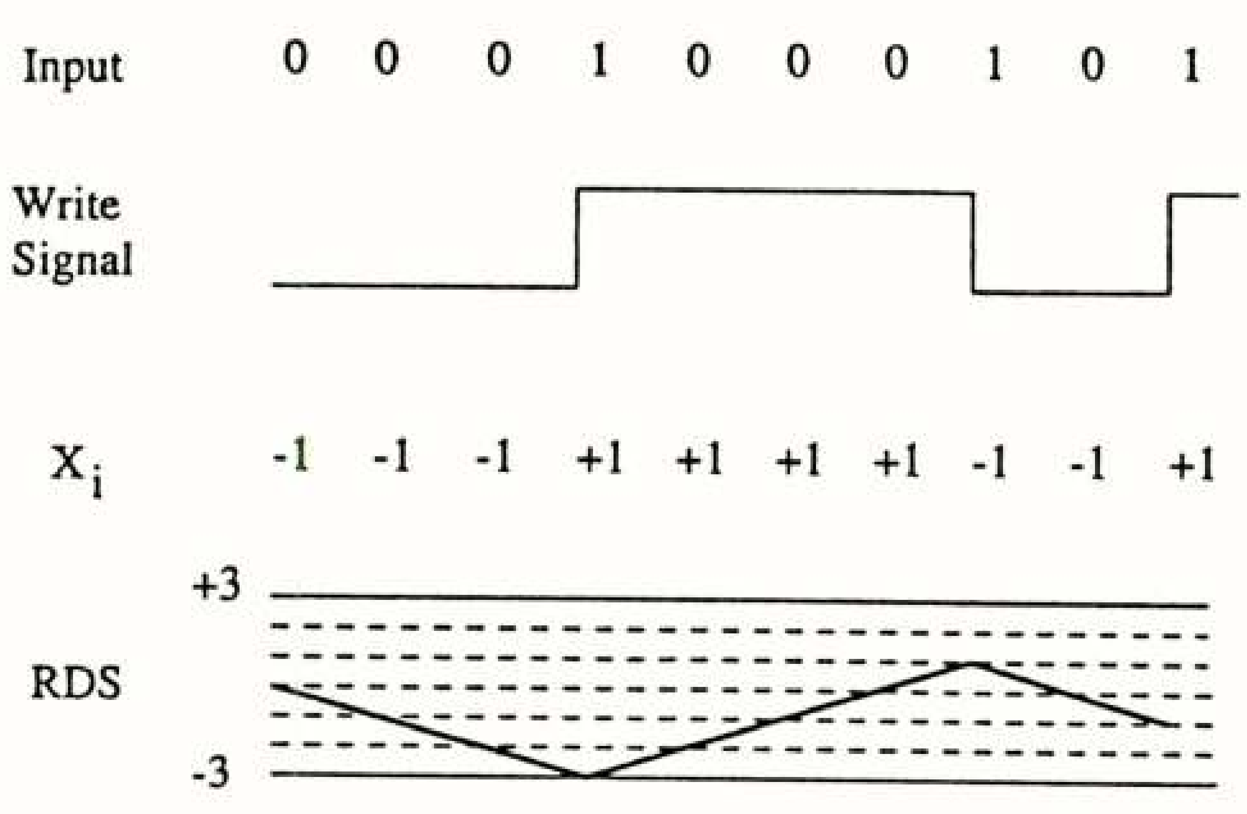

Figure 5. Running digital sum (RDS) versus time. Input symbols (NRZI) are translated into the (NZR) write signal and the channel bits x_i. In this example, the RDFS assumes at most seven values.

Figure 5 portrays the various signals. As an example, the RDS is supposed to stay within the prescribed limits, and as a result the RDS may take at maximum seven values. An essential point (which is not difficult to proof) is that if zi is bounded, the spectral density vanishes at dc. All codes designed to suppress the - low-frequences do so by guaranteeing that the RDS stays within a limited range. In the next subsection, various dc-free code designs will be outlined.

B. Code implementations

Practical coding schemes devised to achieve suppression of low-frequency components are mostly constituted by block codes. The source digits are grouped in source words of m digits. The source words are translated using a conversion table, known as codebook, into blocks of n digits. The essential principle of operation of a channel encoder that translates arbitrary source data into a dc-free channel sequence is remarkably simple.

The approaches which have actually been used for dc-balanced code design are basically three in number:

* zero-disparity code,
* low-disparity code,
* polarity bit code.

The *disparity* of a codeword is defined as the excess of the number of 'ones' over the number of 'zeros' in the code-word thus the codewords 000110 and 100111 have disparity -2 and +2, respectively.

Of special interest are zero-disparity codewords, which contain equal numbers of 'ones' and 'zeros'. The obvious mehod for constructing dc-balanced codes is to employ codewords that contain an equal number of 'ones' and 'zeros'. or stated alternatively, to employ zero-disparity codewords that have a one to one correspondence with the source words.

In low-disparity-codes, the translations source word to codeword are not one-to-one.The source words operate with two alternative translations which are of equal or opposite disparity. During transmission, the choise of a specific translation is made in such a way that the accumulated disparity, or the *running digital sum* , of the encoded sequence, after transmission of the new codeword, is as close to zero as possible.

The third coding method is attractive because no look-up tables are required for encoding and decoding. The (n-1) source symbols are supplemented by one symbol called *the polarity bit.* The encoder has the option to transmit the n-bit words without modification or to invert all symbols. Again, like in the low-disparity code, the choice of a specific translation is made in such a way that the accumulated disparity is as close to zero as possible.

TABLE V
Number of zero-disparity codewords and code rate versus codeword length$n$.

n	N_0	R_0	N_1	R_1
2	2	0.500	3	0.792
4	6	0.646	10	0.830
6	20	0.720	35	0.855
8	70	0.766	126	0.872
10	252	0.798	462	0.885
12	924	0.821	1716	0.895
14	3432	0.839	6435	0. 904

C. Zero-disparity coding schemes.

Probably the most obvious basic method to generate dc-free sequences, and certainly the simplest to describe, is constituted by zero-disparity codewords. In this scheme, each source word is uniquely represented by a codeword that contains equality many 'ones' and 'zeros'. Clearly, zero-disparity codewords are possible only if the codeword length n is even. The number of zero-disparity codewords, No, of binary symbols (n=even) is given by the binomial coefficient.

$$No = \binom{n}{n/2}$$

Table V shows the number of zero-disparity codewords as a function of the codeword length n. Table V also presents the code rate, Ro, given by

$$Ro = \frac{1}{n} \log_2 No.$$

The spectra of zero-disparity codes are shown in figure 6. It can be seen that the spectra indeed vanish and are also small in the neighbourhood of the zero frequency. Note that the frequency range where the power spectral density function is small,the *spectral notch* width, becomes larger when the code word length n and (see Table V) rate of the code becomes smaller. For a wider frequency range of suppressed components, one has to pay more in terms of redundancy of the sequence.

TABLE VI
Simple low-disparity dc-free code.

source	*State 1*	*State 2*
000	0011	0011
001	0101	0101
010	1001	1001
011	0110	0110
100	1010	1010
101	1100	1100
110	1110	0001
111	1101	0010

D. Low-disparity coding schemes

Besides the set of zero-disparity code words, sets of codewords with non-zero disparity are used in low-disparity codes. Source words can be represented by two alternative channel representations of opposite disparity. The encoder opts for a particular channel representation with the aim of minimising the absolute value of the running digital sum after transmission of the new code-word. A simple example of a rate ¾ code is shown in Table VI. The left column shows the list of the eight 3-bit source words. The word transmitted is taken from the column denoted by the State 1 or State 2. Let's say the encoder is in State 1, then, for example the source word '111' is represented by '1101'. On the other hand, if the encoder would have occupied State 2 then '0010' would have been transmitted. If a zero-disparity codeword is transmitted (source words '000' to '101') then the encoder remains in the same state. If, however, a low-disparity codeword is transmitted then the encoder changes state. It is easily verified that, as codewords of zero or alternating disparity are transmitted that the running digital sum of the sequence will be limited. Clearly, the number of source words, N_1, that can be catered by low-disparity codes is given by (n even)

$$N_1 = \binom{n}{n/2} + \binom{n}{n/2+1}$$

Table V shows N1 and the code rate

$$R_1 = \frac{1}{n} \log_2 N_1$$

as a function of the code word n. In the next subsection, we will discuss two implementations of rate 8/10 low-disparity codes, which are applied in the R-DAT and DCC audio recorders.

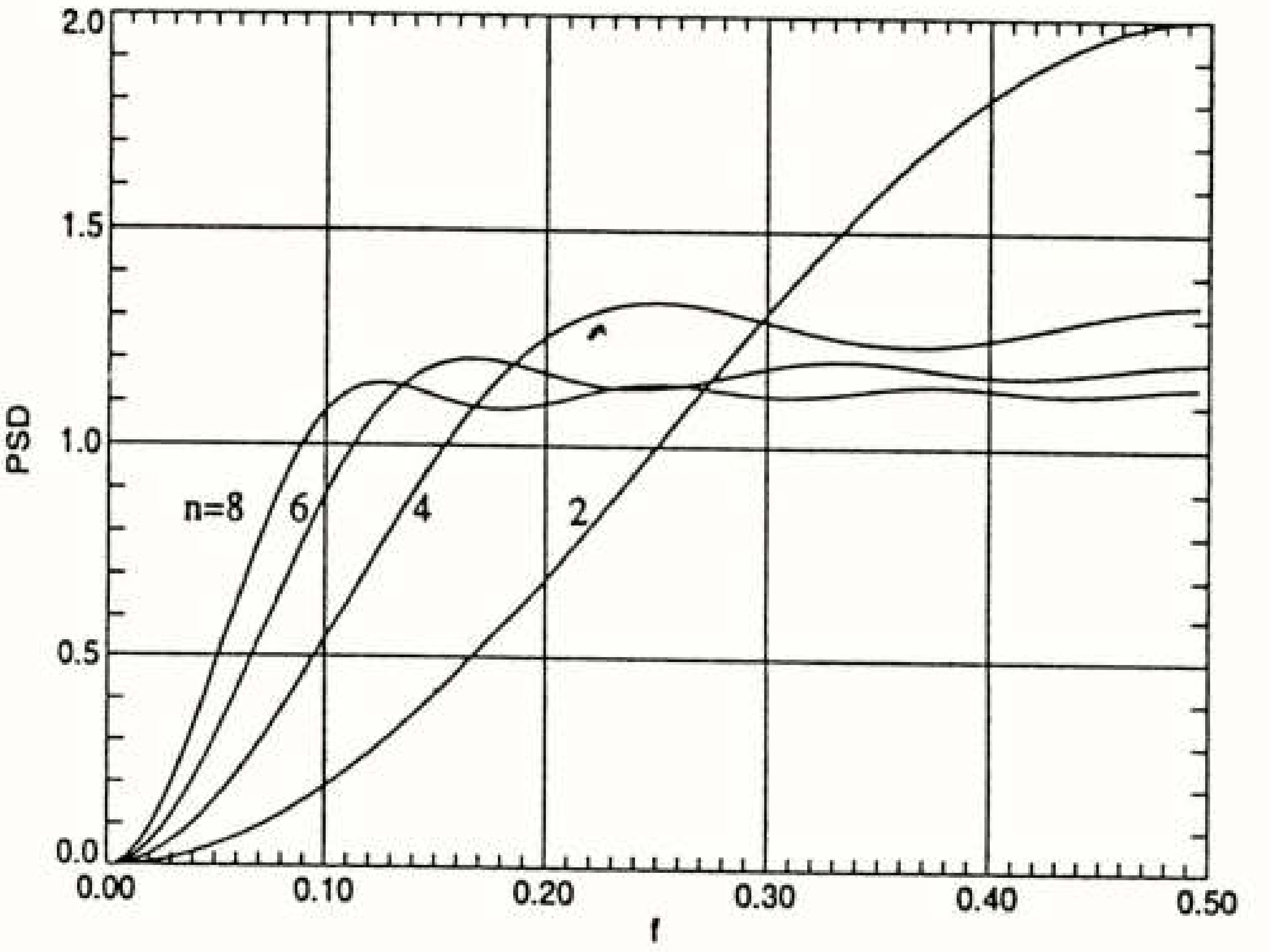

Figure 6. Power density function os zero-disparity codes versus frequency with the codeword length n as a parameter

D.1 8b 10b code

In digital recording on magnetic tape it has been found that a rate 8/10, dc-balanced channel code has attractive features both in terms of system penalty and hardware realisation. Most of the implementations in use are block codes which translate 1 byte (8 bits) into 10 channel symbols. Clearly, a zero-disparity block code is impossible since the number of available 10-bit zero-disparity code-words, 252, is smaller than the required 256. A two state encoder offers the freedom of at maximum 252+210=462 codewords. Because only 256 codewords are required, this evidently offers a large variety of choices. The codebook can be tailored to particular needs, such as minimum dc-content and/or ease of implementation. It is therefore not too surprising that numerous variants have been described in the literature, in patent literature in particular. A code of great practical interest is the 'Fukuda 2' code, employed as the recording code in the DAT digital audio tape recorder [5]. The 8b10b code used in the DAT recorder is designed to function well in the presence of crosstalk from neighbouring tracks, allow the use of the rotary transformer, and have a small ratio of maximum to minimum runlength in order to ease overwrite erasure. Essentially, the code operates on the low-disparity principle as discussed above. The hardware of the encoder and decoder has been reduced by computer optimising of the relationship between the 8-bit source words and the 10-bit codewords [5]. The DCC recorder is also equipped with a low-disparity rate 8/10 dc-free code [6]. The code was designed in such a way that the channel sequence can take at most six digital sum values. The maximum runlength is 5 channel symbols.

5. Pilot tracking tones

Dymamic track-folowing machanisms are at present used in consumer-type video or digital audio tape recorders that aim to alleviate the mechanical inaccuracies of the recorder. In the DVC (Digital Video Cassette) recorder, the the servo position information is recorded at low-frequency components, called *pilot tracking tones* [7]. The principle of the operation is essencially as follows. On even tracks the pilot tone has a frequency f_1 and on odd tracks the pilot tone frequency is f_2.. Servo position information is developed from the read-back signals by subtrackting the amplitude of the f_2 component from the f_1 component. These two components can be separated with band filters since they differ in frequency. As the head moves off track in one direction, the amplitude of one component decreases whereas the amplitude of of the other increases. On the basis of the difference error signal and the contol technique employed, this then instructs the control mechanism.

In other words, by observing the difference between the pilot tone amplitudes of adjacent tracks we can tell wheter we are moving offtrack to the right or to the left. Experiments have shown that adding analog pilot tones to the write current will result in serious interferences between the digital data and the tones. Furthermore, the precise amplitude of an analog pilot tone depends on the characteristics of the head-tape combination, which means careful adjustment of the write current is necessary for each of the heads. This fact precludes the technique, of e.g. simply adding asinusoidal waveform to the binary data. The only option available is to embed the tones in the recorded binary sequence.

A. Description of the 24----25 channel code

The main parameters of the 24----25 code can be sum marized as follows:

* Rate = 24/25.
* Minimum runlength = 1.
* Maximum runlength = 9. This maximum run-length feature is not guaranteed, but the probability of occurrence of runlength larger than 9 is smaller than 5 times 10^{-6}.
* perfectly DC-free, -3dB at $f \leq f_b / 500$.
* Provisions for tracking: (channel bit rate 21 Mbit/s)
  - Pilot tone $f_1 = f_b/90$ (230kHz), SNR $\geq$ 20 dB in 300 Hz.
  - Pilot tone $f_2 = f_b/60$ (350kHz), SNR $\geq$ 20 dB in 300 Hz.
  - Notches around the pilot tones f_1 and f_2 stabilize the amplitude.
  - Notch depth $\geq$ 5 dB (resolution bandwidth 300Hz).

  Amplitude stability within 0.3 dB peak-to-peak.

  Notches at frequencies f_1 and f_2 improve the tracking SNR by reducing the in-track code noise.
* No coding/decoding tables are needed.

B. Tracking format

The recorder system uses two pairs of heads that are diametrically positioned with respect to one another on the drum. The tracking format requires three types of tracks with different frequency spectra. The track types, F0, F1, and F2, are listed in Table VII. The footprint for the proposed scanner configuration is shown in Table VIII. It can be seen that each head pair has one head of type F0 (no pilot tone), while the second head is alternately of type F1 or F2. During the reading of the F0-type of tracks, the crosstalk is measured from the neighboring tracks which are of type F1 or F2. As explained in the introduction, servo position information is developed by subtracting the amplitude of the f_1 component from the f_2 component.

These two components can be separated with band filters since they differ in frequency. As the head moves off track in one direction, the amplitude of one component decreases while the amplitude of the other increases. The difference error signal is used for steering the actuator on which the head pairs are mounted. The spectral notches are required to cancel any interference between the written data and the servo detection system.

TABLE VII

Definition of types of heads

type	notches	pilot
F0	DC, f_1, f_2	No pilot tone
F1	DC, f_1, f_2	f_1
F2	DC, f_1, f_2	f_2

TABLE VIII
Configuration of heads and spectra

tracks	F0	F1	F0	F2	F0	F1
head number	0	1	2	3	0	1

A 'polarity control' bit is stuffed in each sequence of 24 successsive input data bits to create the freedom to shape the spectrum of the encoded bit stream. By setting this control bit to '0' or '1', the polarity of 25 bits at the output of the coder can be chosen. The sender opts for that value of the control bit that minimises the accumulated signal power of the transmitted code words at three predifined frequencies, namely DC, f_1 and f_2. Furthermore, subtraction of the desired pilot tone before 'measurement' of the power at the power tone frequencies, the pilot tone will appear at the output of the precoder. Should the maximum runlength on the channel become larger than the predifined maximum, i.e. nine, the above spectral optimisation is overruled. The resulting spectra are shown in figure 7.

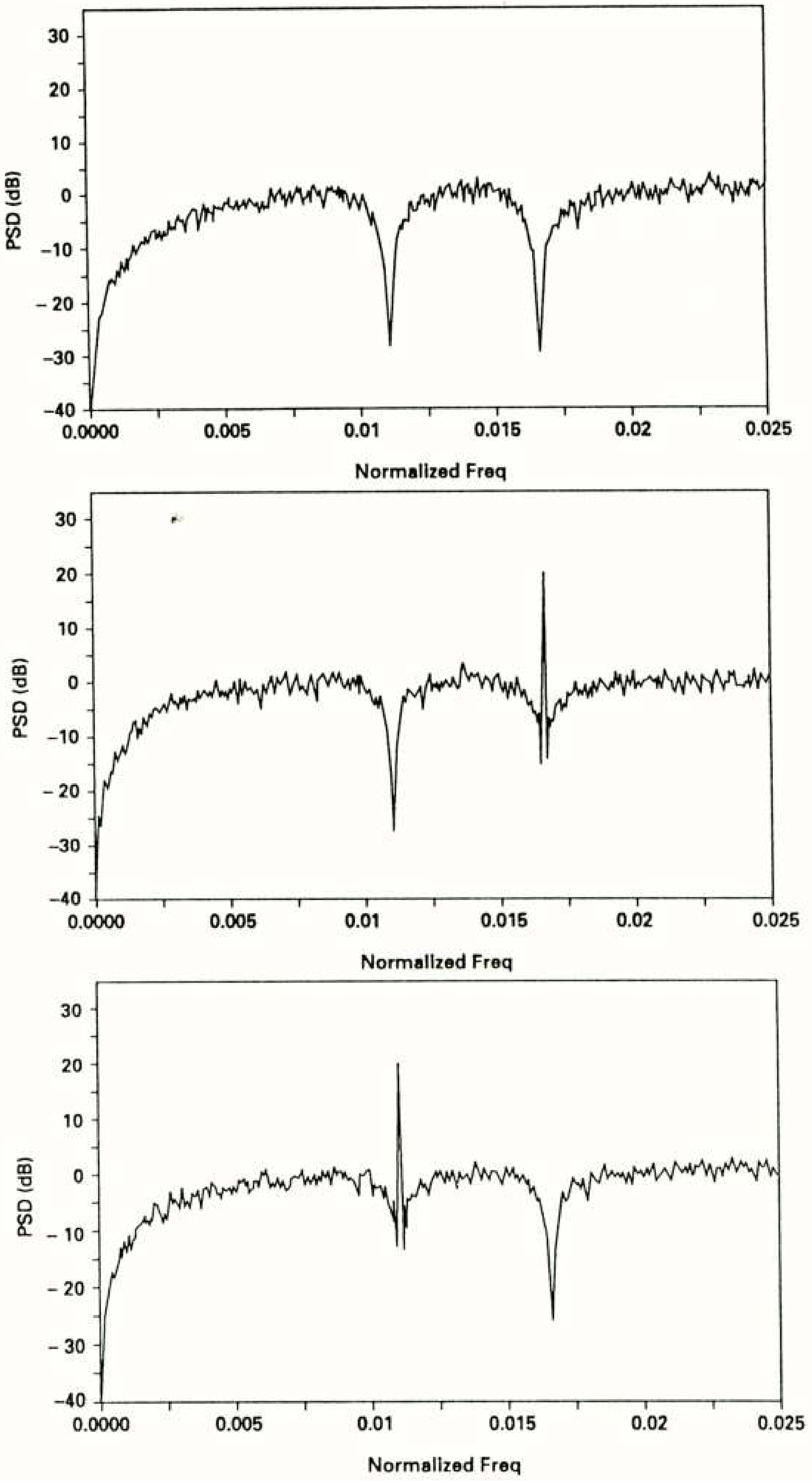

Figure 7 Spectra of the track types Fo, F1, and F2

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Voordracht gehouden tijdens de 452e werkvergadering

From Copper to Fibre, From PDH to SDH/ATM
From POTS to Interactive Multimedia Services

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Abstract
A range of interactive multi-media applications can be realised using the existing networks. To access these applications, the current access network of the Telecom or CATV operator is available. The transportmedia are mostly copper: twisted pair and coax respectively. The transfermodes in general are PDH and analogue techniques such as AM VSB. To fully deploy interactive multimedia services (narrow as wel as broadband) however, fibre must be the pavement and SDH and ATM the transfermodes. This certainly does not genericly imply Fibre To The Curb/Home and SDH/ATM in all parts of the access network as the solutions for today. This paper presents both the roll out of Fibre In The Local Loop by PTT Telecom , the stepwise roll out of ATM and Broadband Services as a coordinated action paving the way for the migration from separate PNO's for POTS towards an AT&T Unisource Alliance Full Service Provider.

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1 Fibre In The Local Loop

1.1 Summary

An Optical Access Network is introduced in the Netherlands as an optical overlay network in the primary part of the access network: Fibre City Rings. The rings are rolled out using blueprints in which market information and topographic data is incorporated. Thus, PTT Telecom brings out fibre close to both business and residential customers. The timing of implementation of the blueprints is market driven. Today the triggers for roll out are mainly determined by business customers, but the blueprints are such that residential customers can benefit when multi media services will penetrate this market segment. Following the stages of vision, strategy, policy and design, the actual roll out has started in 1995. The guidelines used to design the blueprints of the Primary Access Network are implemented in a sophisticated computer tool. The architecture consists of 3 to 5 FO rings per Local Exchange Area and implies enlarged availability through dual routing. These Fibre City Rings of different LEA's are coupled if the market requires the feature of dual homing. Momentarily blueprints are available covering all major cities in the Netherlands.

1.2 Introduction

Within the strategy department of the Business Unit Network Services of the Dutch PTT Telecom, in 1991 the first draft of a strategy for the introduction for Fibre In The local Loop was developed. Because Fibre To the Home still was an unrealistic goal, the target was to install fibre in Primary Access Network (PAN) such that the market demand could be served. This resulted in a Master Plan in 1992 stating that FO solutions in the access network ought to be found to serve the changing needs of the business customers from 1995 onward and to create at the same time a basis to accomodate residential customers with new multimedia services from 2000 onward. In 1992, the formation of the PAN-project started. Commercial, technical and operational guidelines were designed within some 14 project groups in 1993. In 1994, on the basis of the guidelines, the blueprints of the FO-rings for the Primary Access Network were produced using a sophisticated computer-tool, pilots were executed and the guidelines expanded and tuned to the findings in the pilots. Thus, all preparations were in place for a major roll out in 1995. However, the large scale introduction of fibre in the access network obviously has a major impact on all parts of the organization. Firstly, the position of PTT-Telecom on the Dutch market rapidly changes through liberalization and competition so that broadband services for business customers become cheaper, gain quality and will be easily available. These factors obviously affect the commercial departments. Secondly, the technical structure is completely new for the technical departments although the LEX-service areas are (yet) not affected. Nevertheless, these departments were used to plan, work, think in copper vocabularies for over a century. The new network structure is a fibre ring, and not a star structure, with access nodes for 500 to 4000 (future) customers. Thirdly, all major processes (administration, maintenance and provisioning) are affected by the commercial and technical changes. By involving people of the operational districts in every stage of the project the organizational / operational change has been anticipated and incorporated. These commercial, technical and operational aspects, have all had equal attention in the planning process to ensure a smooth roll out; they will be dealt with subsequently.

1.3 Commercial aspects

PAN is a market-driven concept. Within the blueprints all current market information and market prognoses is incorporated; the local marketing departments collect the market data and present the data in a certain format to the planning departments of the telecom district. The actual implementation of a PAN network, i.e. the transformation from blueprint into an existing FO-network is predominantly triggered by the market demands of large business customers, see figure 1. PAN is able to cope with todays and future demands of all business customers, and designed such that through new generations of transmission equipment all residential customers can be served as well. Today, only under specific conditions, residential customers are connected.

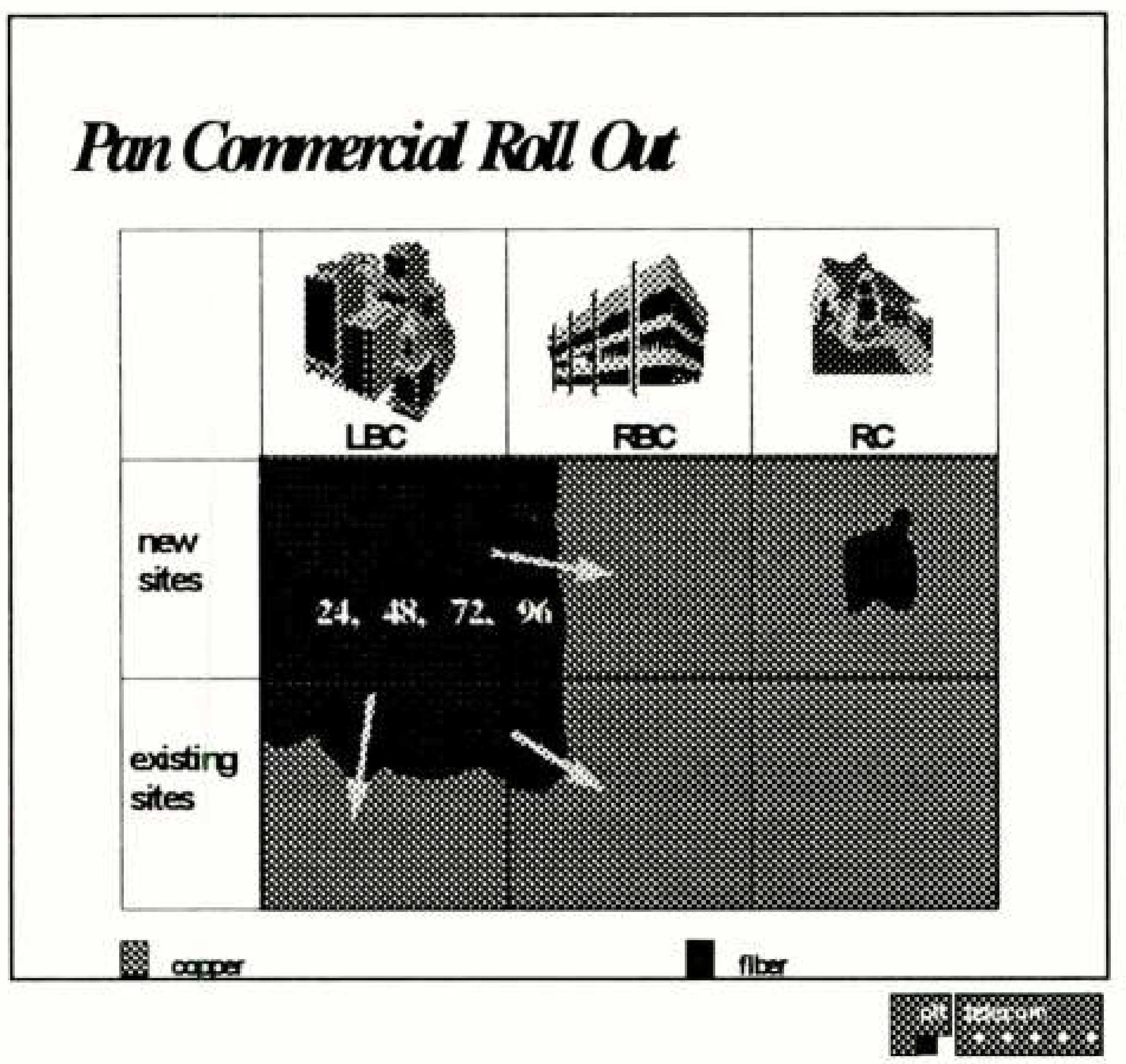

Figure 1: Market driven roll out with focus on the Large Business Customers

1.4 Technical aspects

Among the technological aspects we gather: the network architecture, the planning and designing, the outside plant and housings, the construction guidelines, the selected (transmission) equipment and powering.

<u>the network architecture</u>

Many network architectures have been studied. Principal criteria for the arcitecture were the demands for availability, flexibility, costs and the fact that network had to be future proof and able to serve any future multimedia service both for business and residential customers. Finally, the choice was made for ring structures, 3 to 5 rings in each Local Exchange Area (see figure 2); a fibre-poor concept was adhered. Each ring could count at the maximum some 200 fibres. In each ring 5 to 7 access nodes are installed, where the secundairy network starts to connenct the customers. With the ring architecture enlarged availability is ensured through dual routing; the rings of different LEA's are coupled if the market requires the feature of dual homing.

<u>the planning and design process</u>

For several reasons, the PAN-project requires changes in the planning process. Time to market: New services (eg. multimedia, distributive services) in a competing environment demand a fast implementation of network capacity. Uniformity: The technological change from copper to fibre asks for a new attitude and new skills of the design engineers. In order to be able to adapt the network to the latest developments, it has to be uniform throughout the Netherlands. Uncertainties: The planning process has to start when the technical target structure is not yet definitive. Therefore, the planning process should be flexible and the use of outdated information is a real threat. Costs: Both the investments and the operational costs of the network will be high. Design errors can have substantial financial consequences for the life cycle costs of the network.

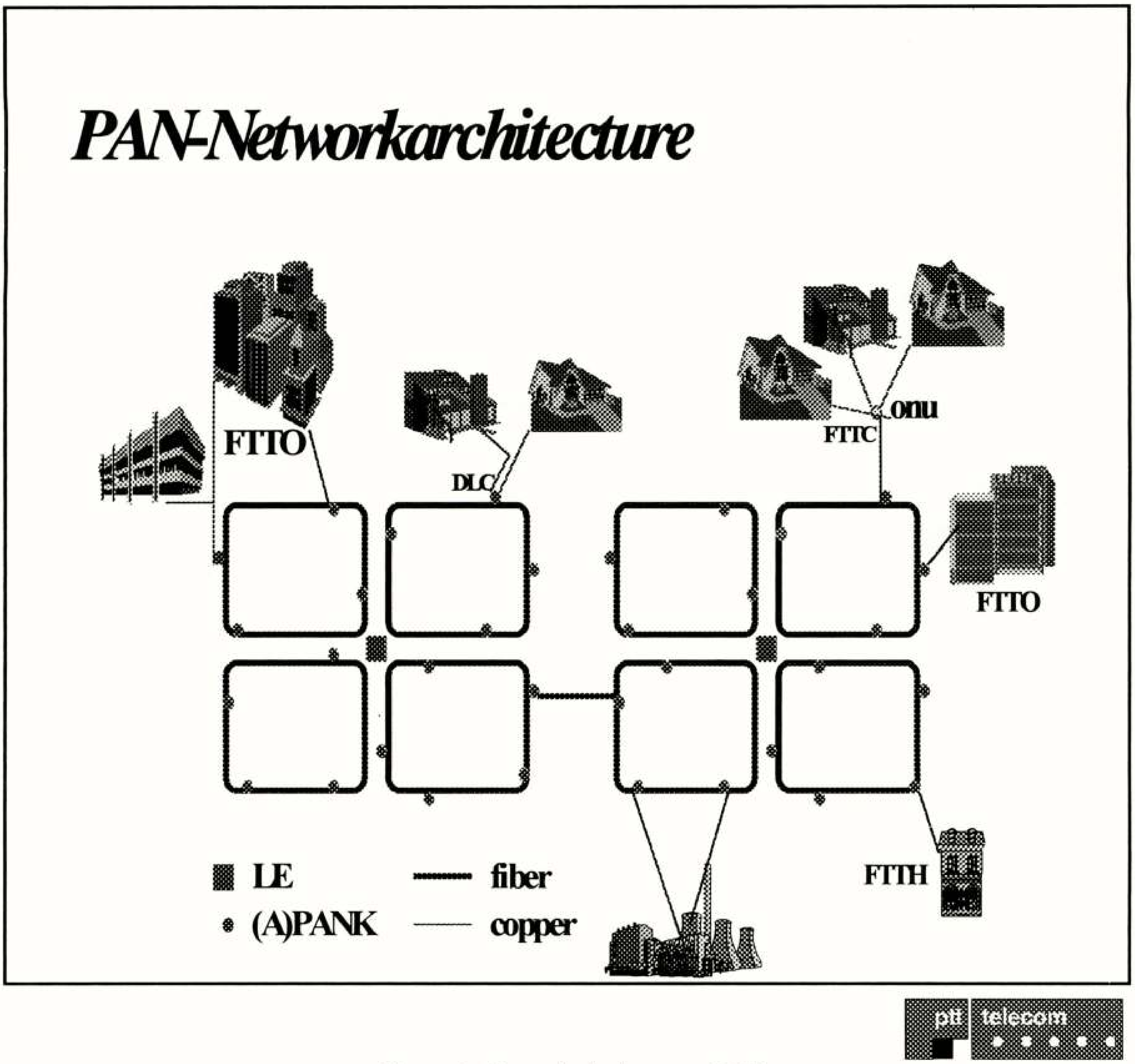

Figure 2: Network Archtecture PAN

The points stated above, show that just communicating the guidelines will not result in a desired, future-proof network. A team of engineers at headquarters, research laboratories and the telecom districts cooperated in adapting the planning process. Several workshops for design engineers were organized to discuss the latest information, and gain acceptance. It has been decided to automize parts of the planning process and standardize the working method and documentation. During the years of implementation the blueprint can be adapted to the 'state of the art' guidelines.

A blueprint, see figure 3, is a design of the primary optical access network in a LEX-area. It serves as a basic architecture to realize individual projects. To support design, PLANTOOL has been developed. PLANTOOL is a computertool which couples general guidelines and actual design. It contains:

- a geographical background;
- cost optimization, using local market and technical information;
- structure editing facilities.

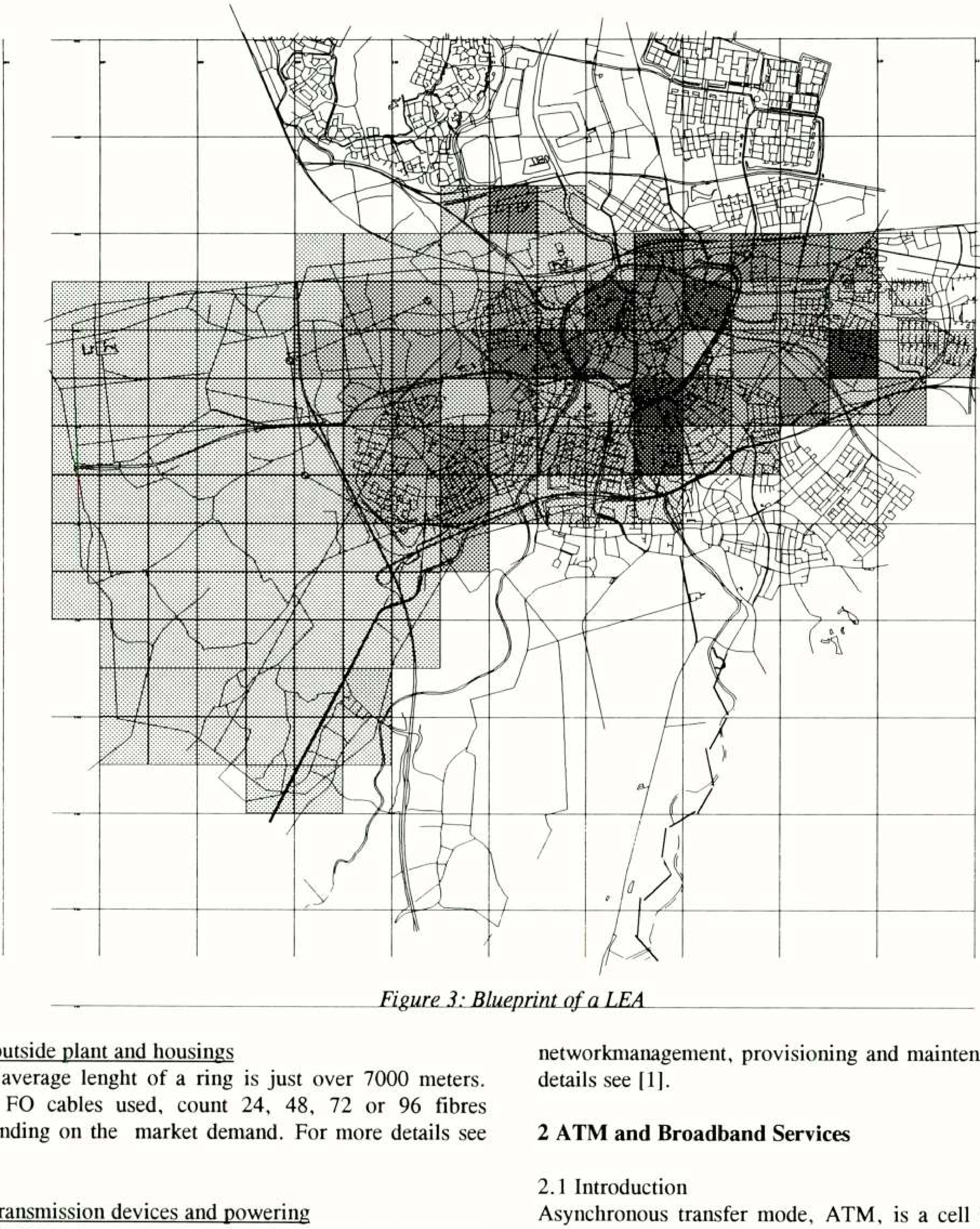

Figure 3: Blueprint of a LEA

the outside plant and housings
The average lenght of a ring is just over 7000 meters. The FO cables used, count 24, 48, 72 or 96 fibres depending on the market demand. For more details see [1].

the transmission devices and powering
The PAN nodes can be 'passive' if they are only used as a manipulation point for fibre connections as is the case with FTTO. In other cases devices such as access multiplexers and line-sytems are installed. In each node the primary powering is ensured using the facilities of the regional power company; for more details see [1].

1.5 Operational aspects
Among the operational aspects we gather: education of the workforces, organization, administration, networkmanagement, provisioning and maintenance. For details see [1].

2 ATM and Broadband Services

2.1 Introduction
Asynchronous transfer mode, ATM, is a cell switched, connection oriented technology that has been selected worldwide to enable the broadband integrated services digital network, B-ISDN. Standardisation of ATM is taking place within the ITU, the ATM-forum and ETSI. The ATM cells contain 53 octets, 5 of which build the socalled header. The asynchronous character of ATM, discarding with the inefficiency and constraints of specific time slots for a specific user, is made possible through the header information.

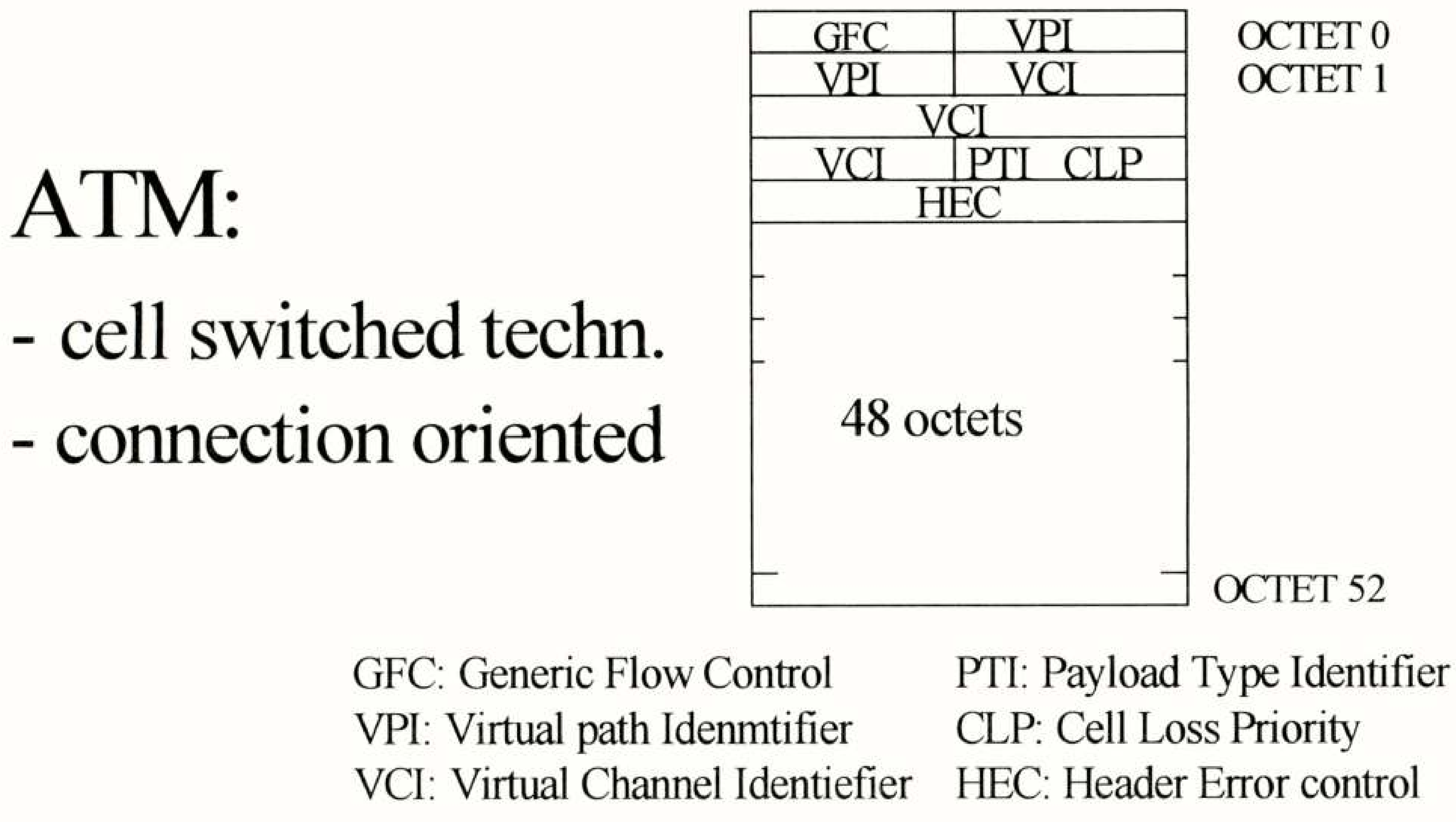

Figure 4: The ATM cell

ATM has been designed as the answer for Full Service Providers, to support transparantly todays and future services. Interactive multimedia services comprising voice, data and video are integrated in a single network. Although today no big revenues are expected and no real killer application exists, customer expectations on ATM are huge. Especially large business customers expect that this technique will provide cheaper solutions for flexible provisioning of bandwidth and interoperability and more or less demand that netwerk operators have this technology in their portfolio, ATM inside, to guarantee future proof solutions. That is why the Unisource Alliance feels it compulsory to plan the introduction of seamless ATM based services, especially since the competition is moving forward quickly. To speed up the implementation, it is necessary to study whether an already existing platform can be used and combined with other ATM developments. Simultaneously, a stepwise roll out is planned of a common ATM platform and Broadband Services as a coordinated action within the Unisource Alliance paving the way for the migration from four separate PNO's for POTS towards an Unisource Alliance Full Service Provider. Obviously, the national plans must be in line with this migration.

2.2 Evolution of ATM and ATM based services

In 1991, several European operators assessed the feasibility of trialing ATM technology and the available ATM standards. Their goals were to accellerate the development of the technology and see whether ATM based services could be offered in a multi-vendor situation and internationally in a multi-operator environment. In the end, 17 operators of 16 countries participated. The pilot ended in december 1995. As a derivative of the international European pilot, national pilots were conducted. This was also the case for the four operators of the Unisource Alliance. Additional goals set by PTT Telecom where to obtain practical experience with ATM technology and first market indications. With the ending of the pilot, phase 0 of ATM has been finilised and a comercial first phase of ATM based services starts. In phase I, the motivation to roll ATM as a technology, is triggered by the business market, requiring ATM broadband services like high Speed Inter LAN, Circuit Emulation and Frame Relay Interworking; a basis for these services is formed by ATM Virtual Path Bearer Services. With the installation of an ATM overlay network in the coming five years for the introduction of the broadband services for business customers, the operators will quickly discover the huge efficiency of ATM on their trunk level. Thus, in addition to a market driven roll out, the roll out will be accelerated by an urge for cost reductions. This can be regarded as phase II: market and technology driven roll out to generate new revenue streams and reduce the costs respectively. As such, the ATM network will gradually bear a substantial part of the traffic and impact and interact with the existing infrastructure. It is then that phase III will emerge. The ATM platform will become the B ISDN platform and interworking with narrow band services will occur. The three phases of ATM are depicted in figure 5. The speed with which each step is taken must be motivated by both strategic motivations and business-cases.

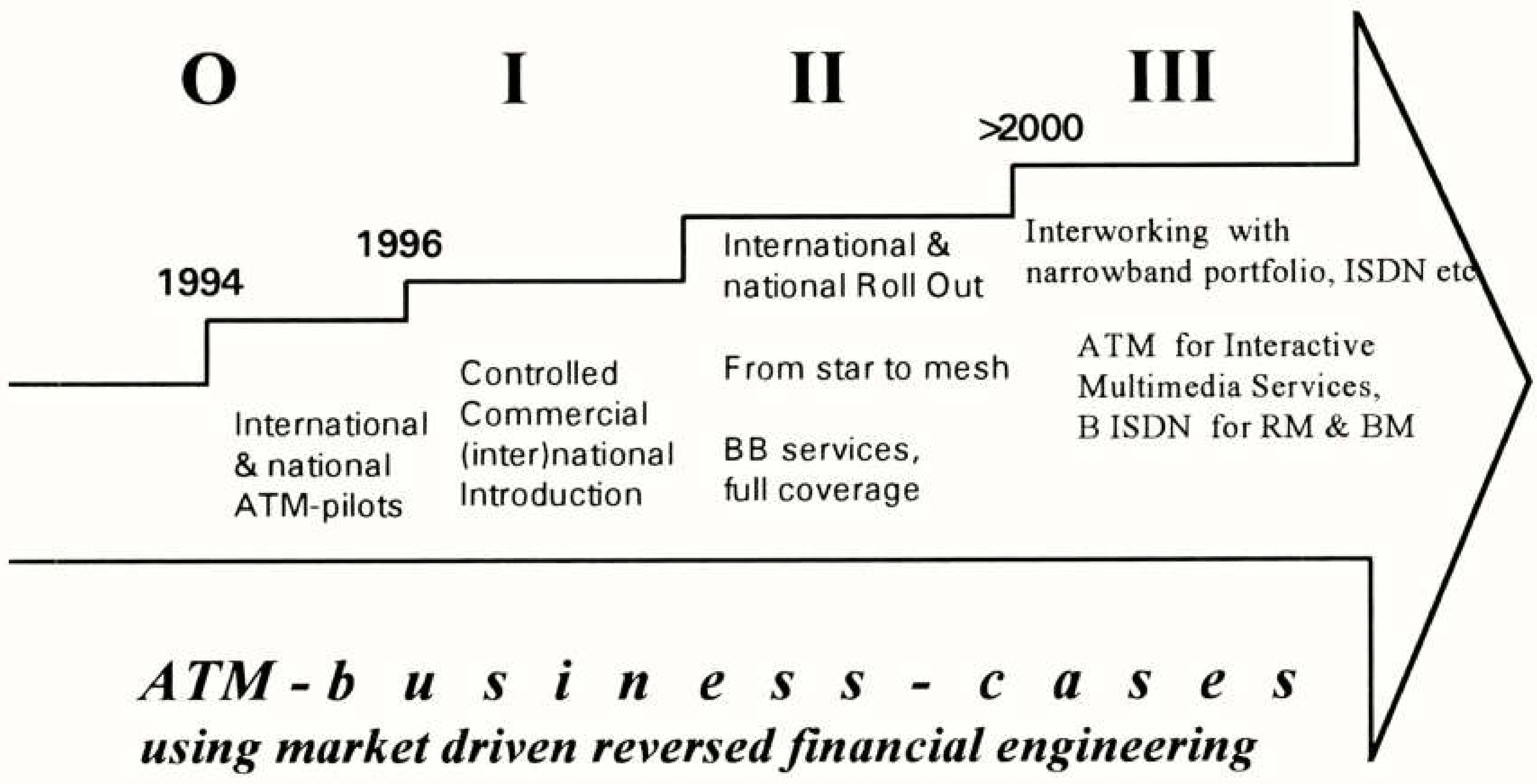

Figure 5. Three phases of ATM

2.3 Phase II, Cost Reduction

It is well known that through SDH large cost reductions can be obtained in both trunk and access networks compared to PDH. This in addition to increased management capabilities and quality improvements. We have proven that under the assumption of a certain increasing demand, the roll out of an ATM overlay network using SDH for transmission is cost efficient, see figure 6.

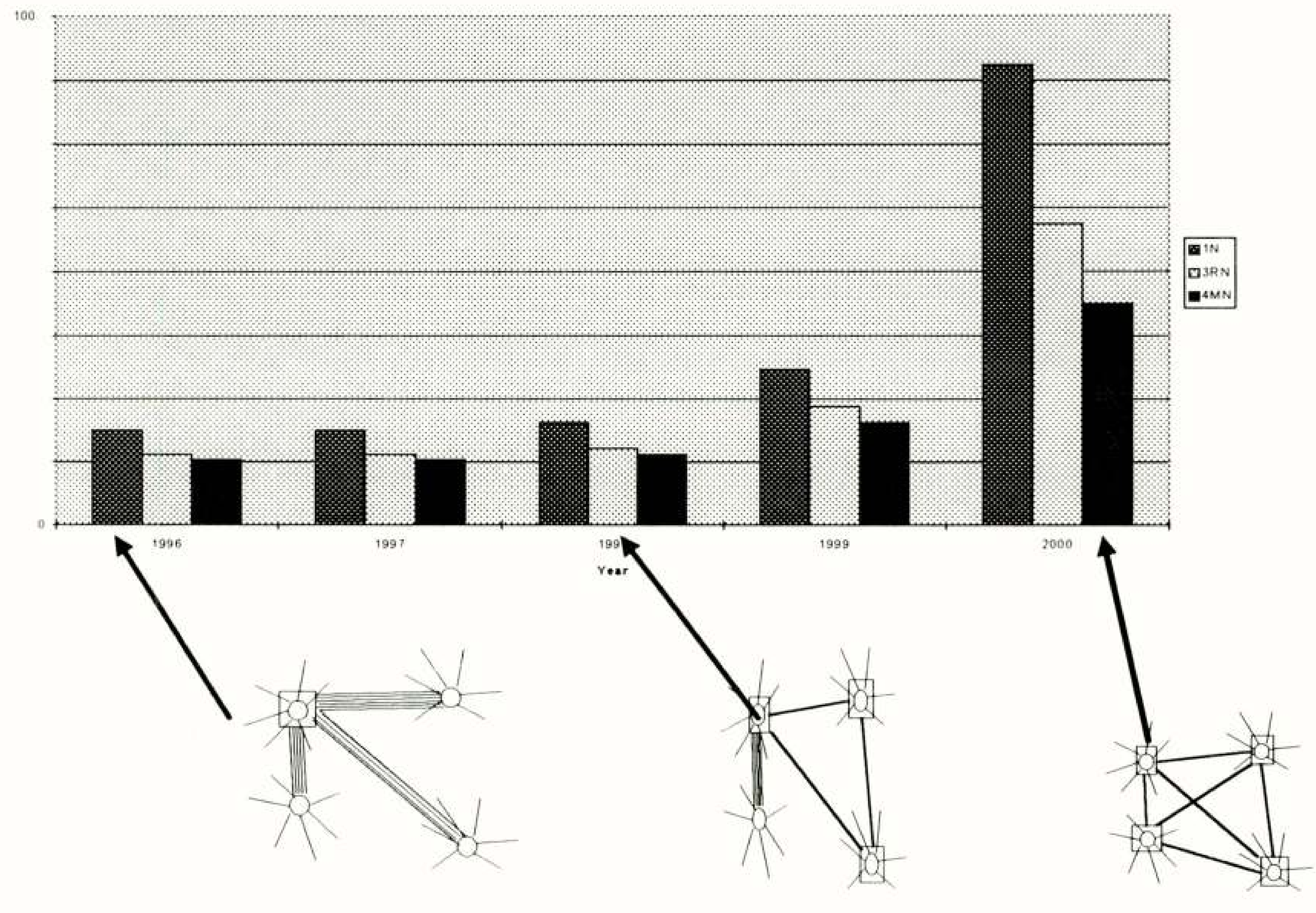

Figure 6: yearly costs for 1996 - 2000 for an ATM-trunk with 1, 3 and 4 ATM cross-connect nodes respectively

3 Conclusions

A range of interactive multi-media applications can be realised using the existing networks. To access these applications, the current access network of the Telecom or CATV operator is available. To fully deploy interactive multimedia services (narrow as wel as broadband) however, fibre must be the pavement and SDH and ATM the transfermodes. This certainly does not genericly imply Fibre To The Curb/Home and SDH/ATM in all parts of the access network as the solutions for today; in the last mile several solutions will be implemented depending on the local commercial (market), technological and operational situation. This paper presented both the stepwise roll out of Fibre In The Local Loop by PTT Telecom (starting with a Fibre To The Zone concept), and the stepwise roll out of ATM and Broadband Services as a coordinated action paving the way for the migration from separate PNO's for POTS towards an AT&T Unisource Alliance Full Service Provider.

[1] PTT Telecom crosses the Copper Threshold; 12th Outside Plant Conference, Ft Lauderdale, Florida, USA, 8 - 15 september 1995, dr N.H.G. Baken.

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In addition to the scientific work he was secretary of the BECOM, a policy coordination board between Philips and PTT Telecom, has been responsible for the coordination of the PTT taskforce "*Exploration of Future Telecom Systems*" , an assignment from the board of directors, and for the organization of the lecture program of the *"Dutch Association of Electrical and Radio Engineers"*
From april 1991. He is working at PTT Telecom and is the project-manager for the development and implementation of a Fiber In The Loop scenario in The Netherlands.. In 1995 he is made responsible for the organisation of the actual roll out of these networks. Within the context of *Unisource* (Telia, Swiss Telecom and PTT Telecom) he was responsible for the Dutch contribution in the Kernel Group *Access Network*.
At the end of 1995 he was asked to prepare the introduction of Asynchronous Transfer Methodology within NWD through organizing the ATM programme, which is now running and amongst others comprises a research programme of 41 manyears, large national and international projects, the latter since he also holds a responsibility to coordinate the ATM activities within the Unisource Alliance
In addition to this work he has been a member of the taskforce Integrated Network Architecture that developed a portfoliomodel for Telecom, and also was involved in a taskforce *Vision Acces Network* . Furthermore, he is an alumnus of the London Business School.

UIT HET NERG

VAN DE VOORZITTER

Op 26 maart 1997 wordt te Delft de jaarlijkse Algemene Ledenvergadering gehouden. Het bestuur legt dan weer verantwoording af aan de leden over het gevoerde beleid in 1996, voor de laatste maal onder leiding van uw huidige voorzitter. Het bestuur heeft prof.dr.ir. W.C. Etten (UvT) met zijn instemming kandidaat gesteld voor het voorzitterschap.

In het Jaarverslag 1996 wordt veel informatie gegeven over het reilen en zeilen van het NERG en de daarmee verbonden organisaties in het afgelopen jaar. Het beleid was onveranderd gericht op het zijn van een goede wetenschappelijke vereniging, sober, maar effectief de ontwikkelingen volgend en focusserend rond de belangrijke ontwikkelingen in het vakgebied. Het genootschap heeft dit jaar voor het eerst in zijn geschiedenis de achthonderd 'echte' leden bereikt.

In het Jaarplan 1997 wordt de koers voor het volgend jaar uitgezet. Ik laat de belichting daarvan gaarne over aan mijn opvolger in een toekomstige aflevering van deze vaste rubriek van Het Tijdschrift.

Zoals bij het NERG gewend, kunnen belangstellende leden aan de administratie vragen om toezending van deze documenten. Voor degenen die daarvan geen gebruik maken, wordt hieronder een summier overzicht gegeven van de inhoud van het jaarverslag.

1. Onder 'Het NERG in 1996' wordt goed nieuws vermeld over de ledenaanwas. Met een uitzonderlijke groei van 111 leden en een normaal verlies van 40 leden steeg het ledental tot 796. De doorlichting van de ledenadministratie is voltooid. De lijst van donateurs bevat ook enkele nieuwe namen.

2. Onder 'Hoofdactiviteiten van het NERG' wordt verslag gedaan over de werkvergaderingen, Het Tijdschrift, het jubileum, de onderwijsactiviteiten en de contacten met de TU's.
Terzijde zij opgemerkt dat er een onderzoek op stapel staat wat moet leiden tot een goed inzicht in de waardering en wensen van de leden omtrent de werkvergaderingen en Het Tijdschrift. Het resultaat daarvan moet gegevens opleveren waarop beleid kan worden bepaald.

2.1. Zoals gebruikelijk is een overzicht van de tien gehouden werkvergaderingen in een tabel opgenomen met o.m. vermelding van de sprekers en organisatoren. Er werd een evenwichtige verdeling bereikt tussen dag- en avondvergaderingen (50%) met regionale spreiding. Het totaal aantal deelnemers was 872.
Nieuw was een werkvergadering bij de TUE waarin geselecteerde studenten een presentatie gaven van hun afstudeerwerk. De beste prestatie werd beloond met een prijs, toegekend door een uit het bedrijfsleven afkomstige jury.

2.2. Het Tijdschrift is weer uitgekomen met vijf afleveringen, waarvan de laatste het overzicht van de promoties in het afgelopen academisch jaar bevat.
De redactie is overgegaan tot een andere werkwijze ten aanzien van acceptatie en 'review' van artikelen.
Ter verdere kostenbeperking is er toe overgegaan de tekstopmaak in eigen beheer uit te voeren met behulp van moderne software. Onderzoek is gaande naar mogelijkheden tot verdere verbetering en verfraaiing van Het Tijdschrift.

2.3. In het kader van de viering van het 75-jarig jubileum is de CDROM '75 jaar NERG' gerealiseerd en uitgegeven en is er ook een prijsvraag voor de studenten van de TU's gehouden. In juni is de Jubileumcommissie door het bestuur onder dankzegging ontbonden.

2.4. De nieuwe voorzitter van de Onderwijscommissie is bezig met de inventarisatie van mogelijke projecten waarmee het NERG het beroepsonderwijs in ons vakgebied kan steunen. Op grond daarvan zal de samenstelling van de Onderwijs-commissie worden herzien.
Voor de examens van Rens & Rens en van PTOpleidingen werden in 1996 NERG-gecommitteerden beschikbaar gesteld.
Naar aanleiding van een verwacht verzoek worden momenteel de voorwaarden overwogen voor erkenning door het NERG van opleidingen en cursussen.
Omdat gebleken is dat er geen belangstelling bestaat voor bemoeiingen van het NERG met onderwijs-op-afstand-projecten, zijn de lopende NERG-activiteiten op dit gebied beNindigd.

2.5. De contactpersonen bij de TU's hebben zich ook in 1996 belast met de ledenwerving onder studenten en collega's, de communicatie tussen het bestuur en de studieverenigingen, de organisatie van werkvergaderingen en werving van sprekers en het stimuleren van artikelen voor Het Tijdschrift.
Er zijn aanzetten gegeven voor het opzetten van een netwerk van contactpersonen bij bedrijven, laboratoria en faculteiten. Zij zullen met instemming van hun directie een brug vormen tussen de leden en het bestuur en zullen activiteiten ontplooien bij het aantrekken van sprekers en auteurs, de organisatie van goede werkvergaderingen en de ledenwerving.

3. Onder 'Externe Relaties' wordt een overzicht gegeven

van de personen die het NERG vertegenwoordigen. Verder wordt verslag gedaan van de activiteiten ontplooid door URSI, IEEE, EUREL, de Stichting NERG/SVEN-fonds enz.

4. Onder 'Financiële Verslagen' worden met toelichting de exploitatierekeningen en balansen gegeven van het NERG en de daarmee verbonden organisaties: Fonds Bijzondere Activiteiten (FBAC), URSI-fonds, NERG/SVEN-fonds).

4.1. Zowel de inkomsten als de uitgaven van het NERG vertoonden meevallers. Hierdoor kan 1996 voor het eerst sinds jaren weer worden afgesloten met een batig saldo in plaats van het begrote tekort.
Door de ledenaanwas werd meer contributie ontvangen dan was begroot. Daardoor hoefde het vermogen niet te worden aangesproken met als gevolg meer opbrengst van rente dan was begroot.
De uitgaven vielen mee door voortgezette kostenbeperking bij administratie, bestuur en redactie, maar vooral dankzij de door allerlei toevallige factoren meevallende kosten van de werkvergaderingen in 1996.
In twee voorgaande jaren zijn dotaties uit het FBAC gebruikt om de tekorten van het NERG te dekken. Daarom wordt het afgeronde overschot van 1996 ten goede gebracht van het FBAC.

4.2. Omdat er in 1996 geen sponsoring van conferenties aan de orde was, werd op het Fonds Bijzondere Activiteiten slechts in beperkte mate een beroep gedaan, hoofdzakelijk voor reissubsidies aan studenten en studieverenigingen.

4.3. Het URSI-fonds had in 1996 een gering exploitatie-tekort. Een reserve wordt gevormd voor de verwachte organisatie van een over vier jaar in Nederland te houden URSI-conferentie.

4.4. Het NERG/SVEN-fonds had in 1996 een exploitatie-tekort dat een derde minder was dan begroot.

Tot zo ver het overzicht van het 17 pagina's omvattende jaarverslag over 1996. De leden en donateurs die alles willen weten, kunnen toezending van de jaarstukken vragen aan de administrateur.

Ondergetekende rest nog allen te danken voor het genoten vertrouwen en de goede samenwerking in de drie jaar dat hij uw voorzitter mocht zijn. Evenals de andere bestuursleden heeft hij de op zich genomen verantwoordelijkheid opgevat als een uitdaging om het mandaat van ons 75 jaar oude, zich steeds verjongend en vernieuwend genootschap aan de opvolgers door te geven met toegevoegde waarde.

Prof.ir. J.H. Geels,
voorzitter i.t.

LEDENMUTATIES

Voorgestelde leden:

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  fax: +44 (0)71 240 8830
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- The InterNetworking Event 97
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- Fifth International Conference on Holographic Systems, Components and Applications
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