Telescope Design. Prof. Ryle.

Obvious mechanical advantage of transit instruments. Difficulty is in N-S aperture. To 2 × ap must then $\frac{1}{2}\tau$ → only $\sqrt{2}$ in S:N.

Nearly-transit observations (e.g. Puerto Rico dish) → cannot track arbitrary objects without missing bits of sky in between → makes obs. programme untidy.

Astronomical Problems

These still determine extent to which design features are compromised.

Galaxy. Most of it resoluble 30′ - 60′ beam. No pressing need for resol^n.

Solar. No sensitivity problem. No multiplicity problem, can use gratings.

Sources.

① Obns. on range of λ → spectra of features.
② shortest pos. λ → accurate positions, $\not\lambda^r$ structure.
③ optimum λ → weakest pos. sources perhaps.
} 3 types of programme

{ S:N ratio, seeing source clear of weak ones behind it

② can → S:N problem too, if weaker sources are of interest. Or extended sources with low T_b.

Also versatility of instrument. Must think of future

Radar. Reqts. are v. different. $S:N \propto \frac{P_{Transm.} \cdot G \cdot A_{collect.}}{T_{syst}} \sim \frac{PA^2}{\lambda^2 T_R}$

Considerable advantage of small λ, or perhaps more realistically on P/λ^2. Radar needs different criteria, & radar suitability ≠ radio suitability. Also only a handful of objects of study, so antenna must be steerable so as not to waste time. Paraboloid is good for this.

② → 10″ arc of interest now.

Fighting against "chance" identifications. Asymmetry not important @ 1′×1′, say.

~ 5″ arc accuracy of finding radio posn. on a sky chart is realistic. Now asymmetry is important & do want a pencil beam. Otherwise "chance" identifications of weak sources (optical) do not mean v. much   Areas v. differently increased by "finding error".

Near normal galaxies. Low T_b. Difficult ∵ flux/beamw. small. M31 needs < 1″ for structure. Can sacrifice a little in resol^n. but sensitivity problem is acute.

Radio galaxies. Lesser. problem pressing.

Spectra. Extend CKL in S and ν. Study red-shift effects, evolution perhaps.

LF. Ionosphere irregularities limit resolution for given instrument.

HF. Situation far away is different from log N-log S. Luminosity fn. wanted.
Fundamental difficulty. Low P obs. are local. High P obs. are distant.
∴ Cannot construct luminosity fn. ρ(P), seeing as log N - log S is so odd.
Have constraints tho, e.g. integrated emission. May be soluble!

Might be worth getting distances alone, irrespective of spectrum. Accept best compromise to get weakest pos. sources. Strong case for this at present.

What are the fundamental limitations? No electronics, no cash problem.

i) Noise from sky, ground.
ii) Must observe thru ionosphere. Irregular structure → scintillation (1km) 3-30 secs. @ night.
iii) Solar rad.ⁿ @ daytime → trouble here. Sidelobe problem.
iv) "100 km → dims. of source perm ~ 5" of time. Longer than τ.
178. $\Sigma_\phi \sim 10 \to 15^\circ$. A.H. showed sidelobes $\sim 25\%/\sqrt{25}$ for 25 points → 5%.
FUNDAMENTAL trouble. Need primary resolⁿ better.
Wedge refraction. Can be corrected by ionospheric soundings. Sunspot min, it's o.k.
→ Limits you to ~ 5000/λ metres.

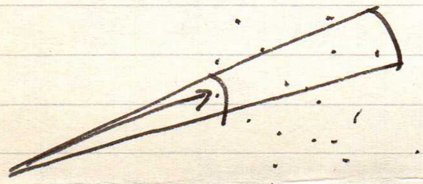
38 survey → $S_{178} \sim 3$ f.u. Limited by the 5000/λ resⁿ in fact.
81.5 → 16× resolⁿ would → S ~ 0.5 f.u.
408 → 8 km telescopes!

i) Rx → $T_R + T_{gal} + T_{atm} + T_{gnd}$ → Total system noise. (Thinking 1 source + Backgnd + Galaxy)

$$\delta T_a \text{ detectable} \sim \frac{1}{\sqrt{B\tau}}\, T_{total}$$

$\frac{1}{2} SA$ must be $10 \times T_{total} \frac{1}{\sqrt{B\tau}}$ at least.

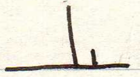
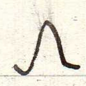
Other limit. No noise, no galaxy, etc, but uniform popⁿ



If go ~ 3.1 times further out, sources are 10% less S.
→ 10% error in the flux of foreground source. Then no. of sources / beam → limiting S_0 for $\frac{1}{10} S_0$ accuracy.

This est → 27 beam areas / source. < this → source > 10% with appreciable probability.

N/ster usefully observable $\sim \frac{1}{30}\, A/\lambda^2$. from this.
Difficult to work out confusion est. precisely.
But P(D) approach → this problem from data explicitly got.
Tells us that D ~ 1.5 – 2 × S of brightest source in beam.
Statistical, tho, so some sources will be in considerable error.
D is like an S, but takes acct. of fact that sources are modified by beam shape if sampled just @ non-redundant rate.
If Dmax is sigⁿᵗˡʸ > noise on record, then info. from P(D) is useful.
→ source statistics, but not individually identifiable ones.
∴ For this, it is well worth being highly confusion limited.

Also posi. error.  scanned with  → 

For ~ 10% source $\frac{1}{2}$ beams away → ≋ 10% posi: error.

To go up ×10 in distance. Area of collecting ×100
resol: ×1000.

Limitations set by confusion predominates in bigger aerials.

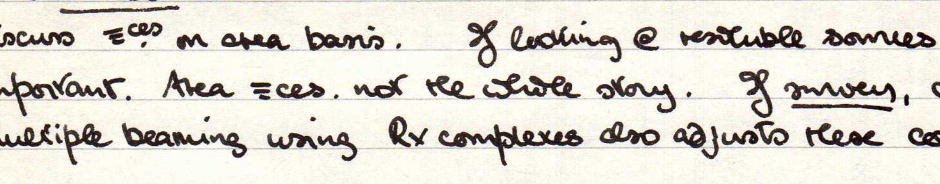
"Effective areas." i) $\omega = \lambda^2/A$ Resolving power. Resolving area ≠ Physical.
ii) Normalised collecting area, by S:N of conventional instrument of same actual area.

Discuss ≡ces on area basis. If looking @ resolvable sources, "driving time" is important. Area ≡ces. not the whole story. If survey, areas are the thing. Multiple beaming using Rx complexes also adjusts these comparisons.

Limiting Effects of S:N & Confusion.
Consider paraboloid ∵ its simplest.
T_R set by Rx → not a fn. of paraboloid.
Assume 1st stage is @ focus, no loss.
primary feed perfect to → ideal illumination. Note, this ≠ uniform illumination, ∵ this → appreciable overspill & ∴ ground detection. If grade it too much to → no overspill, lose effective gain of system. ∴ Compromise.

$$\frac{1}{G}(T_R + T_{gal} + T_{gd}) \rightarrow \text{system noise}$$

Cannot throw away T_{gd}. only far ∵ this → G > & syst. noise eventually <.
Got to be careful with overspill when working off zenith.



500 – 1000 Mc/s. Broad min T_n 80°–100° over all angles. LF lt. is Galaxy.
Can improve this by keeping on zenith, masers, etc.
in 1955, the min was ~ 200 Mc/s. ∴ 178 ⎫ Closest approach to 0.7
1964 500–1000 ∴ 408 & 1420! ⎭ spectrum.

$$\Delta T_n = \frac{1}{\sqrt{B\tau}}(T_R + T_{gal} + T_{gd} + \cdots)$$

Consider $B\tau$ ~ 10 Mc = 10^7
i.e B 10 Mc/s τ 1
τ 1 Mc/s τ 10, say.

τ sets, scanning rate.
B set by freq. alloc: 408 5 Mc/s ⎤
1420 27 Mc/s ⎦

Get ΔT_n min @ λ 50cm. in fact.
How. ΔT_{conf}? Minimise $\Delta T_n + \Delta T_c$. → optimum ν for telescope 1964.5!
For given dish, can plot ΔT_c vs. ν (allowing for spectrum).
100m $\Delta T_c + \Delta T_n$ min @ 16cm. Note that this depo. on B, τ, etc.
↑
awkward to work out precisely, as it knows in advance what logN-logS is

In fact, on best guess about source cts., all sizes of instrument optimise ~ λ 25cm.
∴ Any instrument, whatever the size, best ~ 25cm. for minimum noise T_{total}.

Again, remember that B & τ fixed in this calcⁿ.
B & τ limited in various ways, tho, & even → range available → 15-30 cm perhaps.
Not true that 1000' dish with 3cm maser is the best. 1000', yes, but 21cm!
Fallacy is in source cts, perhaps, or not allowing for 0.7 spectrum of sources.

Dish 1000' @ 21cm. Still not v. good resolⁿ. tho!
Structural problems. Servo-corrected structures, gravity loading might be avoided
Always wind troubles!
↓
of adequate complexity, ν_{nat} ~ several seconds. Will have trouble with wind. Gust structure < 1sec. Cannot stabilise this << ν_{nat}, except using huge powers for rapid acceleration. 1MW to run telescope! Can stab. against gravity loading tho', but this isn't always the main one.

Arecibo pretty good in most respects. Steps forbids full aperture, but this means overspill unimportant. All that happens is beam degradation.
But its beam is not ideal for source structure.
Unfilled apertures are more versatile.
For them, can get better resolⁿ. & ΔT_c limits >.
Possibility of working on longer λ → less structural problems, ∴ bigger inst.,
∴, up to a point better ΔT_N!!
This eventually converges of course, but shows that synthesis can well afford to go to higher wavelengths than brute force paraboloids!

178 area ƒ @ $\Delta T_N \sim \frac{1}{3}\Delta T_c$. O.K. for us ∵ we have P(D) methods.
↓
not opt. ∵ 1.8 slope went on longer than 3C ⇒
+ preamps improved greatly.

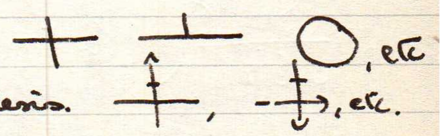
/

Fix collecting area & juggle with shapes → unfilled apertures.
S:N same, but ΔT_c much less ∵ of better resolⁿ. Balance bet. resolⁿ. & S:N shifts to higher λ.

"Filling factor" = $\frac{A_{sensit.}}{A_{resol^n}}$

Resolⁿ → ΔT_c. Choose collecting area s.t. $\Delta T_N \sim \Delta T_c$ (not using P(D)).
make $\Delta T_N > \Delta T_c$ if P(D) also to be used.

2 Distinct Classes of unfilled instrument.
i) all elements physically present → electrical synthesis
ii) not .. .. at once → computer synthesis.



All systems ≃ same in S:N for given area of sky & observing time, see A.H. lectures.

300 m dish → 1′ @ 5m.
@ 25m, collecting area can be down by ~1/4
filling factor ~ .2% !

Design to resolving power. Get sensitivity req^d. later, not knowing time / beamwidth involved.
At high. resoln., always the unknown factor of cosmology. Have to guess eventually.

Obns. in two classes. i) Well resolved. $T_{surf.}$ small, not much S / beam area
ii) Not resolved or only just. T_s great, plenty of S / beam area.

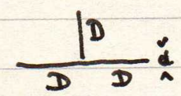
4C 30′×20′ 600/ster @ 2 f.u.
Suppose want 10^5/ster, a ~ 1 source / 30 beam areas. Want ∴ ~ 2′×2′
300m dish, λ10cm.
Sensitivity? We'll guess $N \sim S^{-1.0 \to -1.5}$.
$S_{178} \sim 0.01$ f.u say.
$S_{3000} \sim .001$

Aerial temp, $kT_a = \frac{1}{2}SA \sim \frac{1}{2} \times .001 \times 10^{-26} \times .6 \times \pi\, 2.25\, 10^4 \to 2.10^{-24}$ K
(.6 ↑ efficiency of paraboloid.)

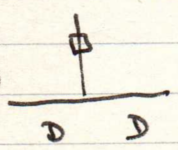
Suppose want to see such a source with S:N of 5 (forget conf. for mt.)
$T_{syst.}$ 100°, say. BW 10Mc/s.
Want fluct^n. $\sim \frac{1}{\sqrt{10^7 \tau}} \times 100 = 4\, 10^{-3}$ $\tau \sim 70$ secs. Must wait this long / no.
Want ~ 4 nos. / beam in each dir^n. ~ 16 nos / beam area.
Want ~ 4τ / beam area. → 280 secs / beam area.
(Different if you know where sources are, this is for surveys, where we don't & must wait)

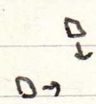
Fully-filled ap. □D. 100% eff^y (Not ⊙ D, note. This has less area & smaller (.6) efficiency). ①

Synthesis ▭ d, ↕2/3d. D long ③

T  ②

① S/N ~ D^2
② ~ $2\sqrt{Dd}.\sqrt{2Dd}$ Great:1 → 3Dd
③ $2Dd.\sqrt{D/d}$ → (3) $D^{3/2} d^{1/2}$

④  $S/N \sim 2\sqrt{2Dd.d^2}\sqrt{D/d} \to 3Dd$

⑤  $\sim 2d^2\sqrt{\frac{2D^2}{d^2}} \to 3Dd$

What sort of vals. of d/D wanted? 300m ⊙ @ 10cm. the criterion, remember 280 sec/bw.
On λ40cm → 4 × area filled. S:N 3:1
D 1000 m., $3Dd \sim \frac{1}{3}4.10^4$ ∴ d/D ~ 1/2%. o.k.

Quite narrow arms, then, given same tobs & same S:N, optimising λ each time.

Earth rotⁿ:

(R) Transit instruments. T style Rx Scan by earth rotⁿ.
τ must be set by this. $\sim \frac{1}{4} \cdot \frac{\lambda}{D} \times 24 \times 3600$ secs.

Per beam area, spend $\sim 4\tau$ ∴ must scan strips not more than $\frac{1}{4}$ beamwidth apart.

(2) [ ] . 4τ again.

(3) ═══ 4τ. Essentially very similar.

All of these give long thin strips of sky. Nothing can be done about this.

(4) Can run the little one along long arm @ $\sim d/\tau$. Need only spend τ in each posⁿ.

Every source remains in reception pattern for longer time (λ/d comes in, not λ/D).
∴ Effective τ is increased from τ to $D/d \times \tau$. This → same as before was.

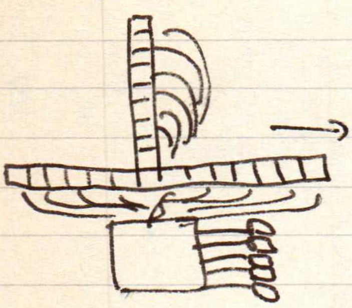
(5) ↑ Successive 24-hr posⁿ for each posn of other one.
Can use $\tau \sim \frac{1}{4}\lambda/d \times 24$ hrs.

S:N $\sqrt{\frac{D}{d}}$ better, observing time < though, by $\frac{D}{d}$, ∴ S:N better by $\sqrt{\text{obs. time}}$.

(4) & (5) are 2 extremes of 2 el synthesis.
Extreme cases of sensitivity & obs. time.
(5) is inconvenient ∵ of amount of data. Must do all sky virtually.

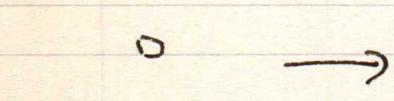
Hence supersynthesis. Now do a selected area of sky by (5) in effect.

Multiple receivers.



Observation rate bettered.
↓
Beam NS arm → diff declinations.
EW arm → betters S:N by $\sqrt{N}$ where N Rxs used.
No betterment in the scanning time.

This sort of technique makes the large semi-filled arrays worth considering seriously.



Simultaneous synthesis. Join & correlate SN $d^2\sqrt{N}\sqrt{D\tau/d}$
or multi-beaming. correlate & join. $\sqrt{d^2 D d N \sqrt{N}\sqrt{\tau}}$

Difficulty of multiple beaming is i) failure rate
ii) cost – must use proper quality individual elements
iii) restrict Rx no → bigger aerial els / channel → d bigger.
1-Rx Synthesis easily breaks even on most of this.

Supersynthesis.

i) S:N good ∵ of long tracking time / bit of sky.

ii) 1-d synthesis cpr. done for you by Earth rot.ⁿ Time fixed @ 12ʰ.

Limited in this respect.

Geometry P.A. O'Brien M.N. 113, 5 (1953). Solar work. 1st first of syn.

EW or NS? Want to avoid low δ ∵ of atmospheric effects.

Really need 2 of them to get full coverage, with N-S resolⁿ as well.

Trouble with sidelobes if use a 2-way mock-up. O.K. for Sun, but not for a deep survey.

N.S.

Must have complete Δ synth. If leave out some, then get -ve pattern of

This last resolⁿ one way but not other → streaks of opacity across the field. Not worth it. Could overcome by grading but this degrades the area for resolⁿ & S:N.

Settle for E-W one

- ACN 1960. N-pole with 178 to obviate tracking. ~ 4° diameter.

→ more or less symmetrical beam ∵ blox used ~ rectangular.

Inevitable moving by distance = d, not the best 2d/3. ∴ Got grating overlap.

O.K. for centre of map, but cannot move out far off primary beam.

Strong source near edge of beam showed up sidelobe effect.

Perhaps even a little better than ought to have been expected ∵ the aerial els. were all different & "may not be perfectly phased"!

Trial S-Syn. Circular area out every 100 days. Total survey time same as any ⊥ system

Saving in steelwork.

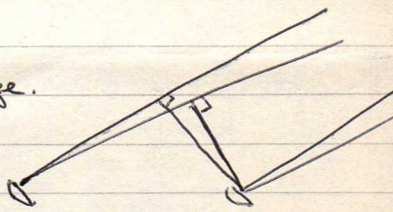
Travel speed on racetrack reasonable.

- Practical Points.

i) Away from N pole. Tracking instruments wanted. Expensive if large.

ii) Bandwidth effects. Need ~ 1/Δf equality of paths.

Even the ΔΘ obs. limited by this



Sky @ edge of beam → attenuated ifference pattern.

Diffⁿ of pass-band Δf.

Need to ensure that $\Delta f / f < d/D$. not to run into this effect.

Want to balance the conditions really. Can get sidelobe suppression this way. Choose d carefully tho as it turns out to be rees. for allocated Δf.

Sidelobe Responses.

ΔA, Δφ per unit. Can around 20% ΔA ≡ 10% Δφ.

If ΔA / φ is x%, total "sidelobe level" is ~ $\frac{1}{\sqrt{N}}$ x%.

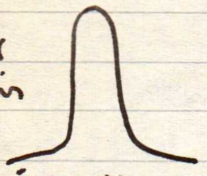
"Calibration sources" take out track ΔG (Rx) from time to time. — Not so easy with Mills + where the long beam is narrow. May not see an intense S every day

Much easier to get @ Δφ if only 2 els. If 110 els, no intrinsic problems of φ checking, but the complexity of feeder system makes it difficult in practice.

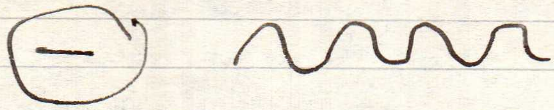
Short-term $\Delta\phi$ not so important in 2-d synthesis ∵ the no. of posns. is eff. much larger.
If 10 posns 1-d → 100 2-d ∴ a ~10-factor in the sidelobe level due to $\Delta\phi$ random (several mins, rather than 24 hrs!)
↳ cable changing.

Suppose 1 posn. left out for 100 posns.

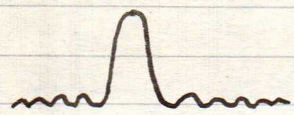
Linear Synthesis



"null" beam δ



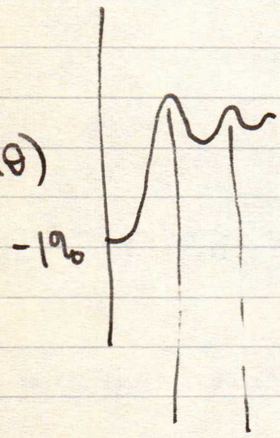
~1% left out

→ 

.1% all way until clobbered by p.e.r.p.
Clobbering depends on config. of missing position.

2d

Error $P(\theta)$



← Bessel fn. fall-off. Get weaker as you go out

→ a "circle" around each source.
Falls off away from source
But cover a lot of sky area.

Which is really more important. Linear const. amp, const area lobes, or Bessel modulated increasing area lobes, ultimately depends on N(S). If $N \sim S^{-1.0}$, then there is not much in it. If $N \sim S^{<-1.0}$, Bessel sidelobes are preferable.

Incomplete path compensation.
Suppose dl left uncompensated $\frac{2\pi dl}{c}(\Delta f) = \Delta\phi$ across BW.

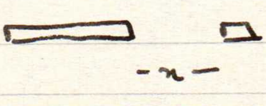
If this $\Delta\phi$ got to 2π, no record at all!
Must make dl v. much less than dl_{crit} $\Delta\phi \to 2\pi$. Not dep. on f, only Δf.

long reception pattern $\Delta\theta$. $l\cos\theta - l\cos(\theta + \Delta\theta) < c/\Delta f$ l = interf. spacing.

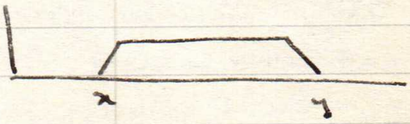
$D/d < f/\Delta f$.

Sampling rate. May have to get rid of interference pattern to reduce sample rate.
Can do this by further path compensation.

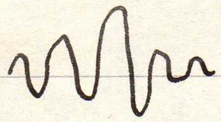
178



Spatial passband

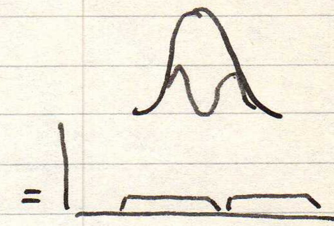


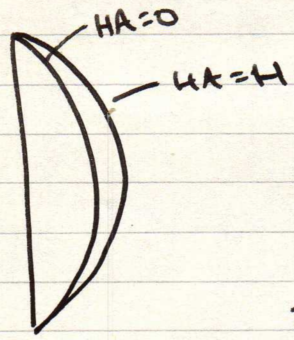
→ Freq. response as Earth rotates.

→  record, not .

Blurred yet again : $\underline{\underline{\Delta\delta}}$ in the long beam & the "quasi-period" of the fringes is anyway ~ To $\sin\delta$.

McAdam. Lower Culmination shows at high δ.
Better o/p difference pattern & get $\underline{2}$ narrower responses.





$$\phi = \frac{2\pi L}{\lambda}\cos\delta\sin H$$ P.d. to 2 s/ages aerials.

$$f = \frac{d\phi}{dt} = \frac{2\pi L\Omega}{\lambda}\cos\delta\cos H$$ Ω = Earth.

$= 0$ for $H = 6^h, 18^h$.

$$\frac{df}{dH} \equiv \left[\frac{df}{d\alpha}\right] = \frac{2\pi L\Omega}{\lambda}\cos\delta\sin H$$

$$\frac{df}{d\delta} \rightarrow \frac{2\pi L\Omega}{\lambda}\sin\delta\cos H$$

$HA = \pm 6^h$, No var. with δ. $$df/dH = \frac{2\pi L\Omega}{\lambda}\cos\delta . (\delta H)$$
$$= \frac{2\pi L\Omega}{\lambda}(\delta\theta) \text{ in sky.}$$

$HA = 0^h$ $df/dH = 0$. $$df/d\delta = \frac{2\pi L\Omega}{\lambda}\sin\delta\,(\delta\delta)$$
$$= \frac{2\pi L\Omega}{\lambda}\sin\delta\,(\Delta\theta)\ \delta \text{ in sky.}$$

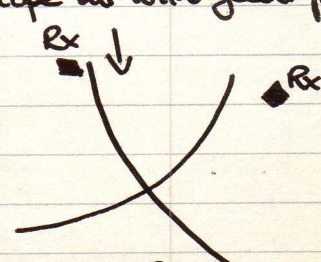
Must sample @ rate ~ $\frac{\lambda}{2\pi L\Omega\,\delta\theta}$. Nothing can change on record faster than this.

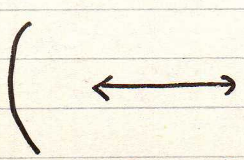
$\sin\delta$ depce of course ≡ to decrease aperture with δ. Area ~ $A_0\sin\delta$.

Benelux. MK1 ended up as Bologna, versions 1 – n.

Mills cross +

Benelux II, IIa, III
van Hoerner $d/d(\cot)$ approach – Cross-type telescope but with feeder problem lessened.
I.R.T. USSR proposal.

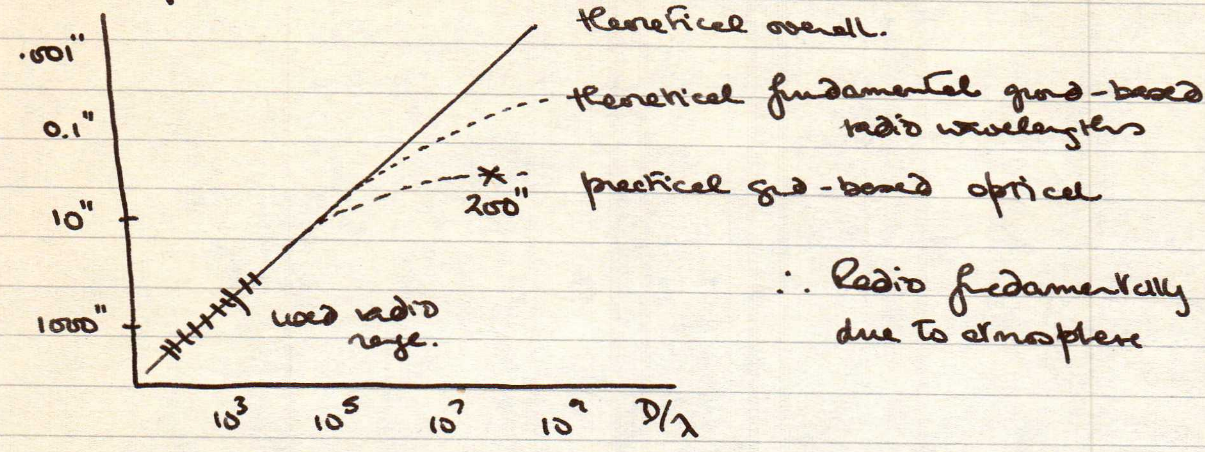


Pulkova. 

Wood + Glue !

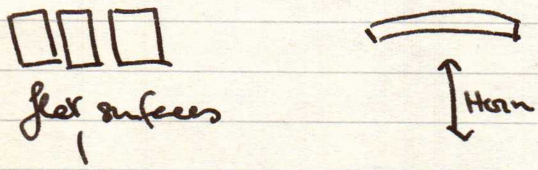
To scan need diffr. focal lengths. tip the reflector → move Rx.

I.R.T. report



∴ Radio fundamentally better due to atmosphere

1"–3" resolution? + sensitivity.
Sens. reqd. → cosmology again.
Considered



approach

Why not curve to mean focal length?

Resolution 1-way only @ low elevation.

What are sidelobe responses?
Air path for phasing the array. May be better than cables.
For low λ, worry perhaps about air losses, & also air radiation.
Ought to be more worried about primary horn pattern. Spillover → a lot of gnd.
~ parameters considered R ~ 10 km

~ 500 panels, ht ~ 100 m width ~ 30 m
Bw → 1" @ 10 cm.
→ 10^9 galaxies (how on E does he know?)
~ 3.10^6 tons + 500 2-d accurate gearboxes.
M.R. estimates min poss £500/ton. Each el ~ 1 J.B.! → £1.5×10^9.
Only need 1 Rx!
Difficult to use more than one Rx, & get any rapid scanning or Rx-based economy.

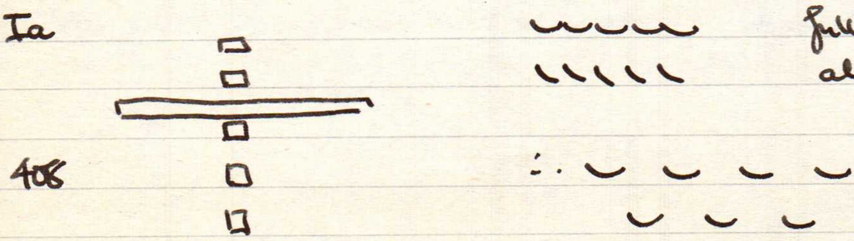
Mills +. Cyl. par. Arms 1600 m ~ 13 m wide 408 × 111 Mc/s.
2.8' 10'

D = 800 m, d = 13 m

Apple Rx. Pl amps distrib. 177 + 22 xtal mixers.

$$S:N = \frac{3\times14\times800}{1000}\sqrt{N}$$

Benelux Ia



fully fills 1 cm a zenith
all look @ each other

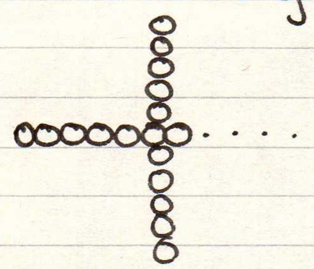
one side
other.

No info. lost. None redundant.

Expense over end-Towers. These are more expensive than middle ones, ∴ you want to cut down on constr^n. rigor somehow with all this no. of them.
Unwanted grating responses from the : ones, cut out by having a <u>mixed</u> long one whose response ↔ brings them down.

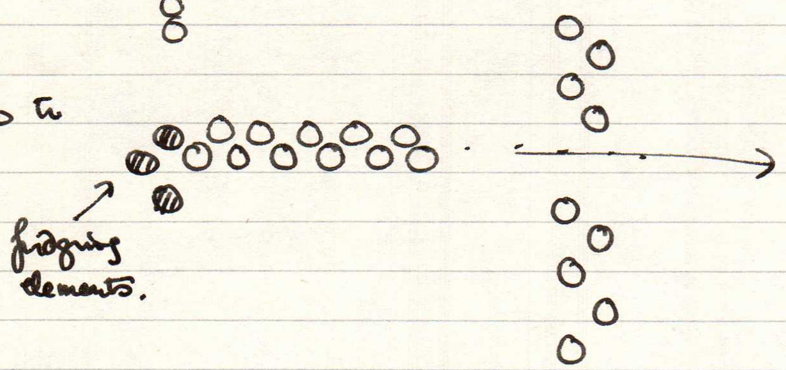
Bologna D ~ 600m Xtal mixers. S:N $\frac{3 \times 600 \times 35}{1000}\sqrt{N}$
d ~ 35m 408
Slightly better than Mills if N same. But Mills has N large.

Benelux II.
Rethink. 21cm. instead of 408 Mc/s? Cyl. par. <u>out</u> @ this λ.



not poss. ∵ they touch.
Also not all arms filled.

<u>Must</u> go to

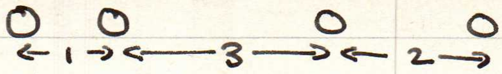


Middle? Haris, but they worked it out, & it came to ~ 71m paraboloid missing. ∴ build one of these elsewhere
<u>Sensitivity</u> was lacking though — very lacking.
Try scanning a little way — it's cheap. This → bigger τ.
But cost diverged faster than S:N was obtained.

Supersynthesis considered.

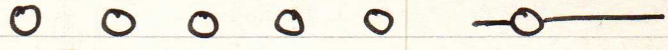
Allscan. All pairs suitably joined.

4 dishes → 6 spacings →



Unfortunately this doesn't continue very far.
Cannot fill all gaps except by using one movable somewhere.

Benelux III.



<u>Uneconomic</u> cf. L's B. but it observes faster.
1500m × 25m dishes. → £1.5 × 10^5 D ~ 1500m d ~ 25m
Xtal mixers still to be used. Claim mixers ~ 600°K with low IF.
This throws away some of the factor gained got by 10 × dishes.
Paramp ~ 200°K – 100°K easily. 3 paramps not too difficult.

Benelux better for detailed strong structure. i.e. where sensitivity important.
Better ∵ faster. Takes 1/6 time → 1/4 S:N.

If Benelux votes same time (looks @ all 6x) → S:N 0.6.
Also they have not looked @ so much sky @ end.
∴ They are mining it by not going far out to paramps.
As it is they'll only be better where S:N not important.