



INTERNATIONAL ATOMIC ENERGY AGENCY  
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION



INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS  
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 294281/2/3/4/5/6  
CABLE: CENTRATOM - TELEX 460892 - 1

H4.882/164 - 08

# WORKSHOP ON CLOUD PHYSICS AND CLIMATE

23 November - 20 December 1985

REMOTE SENSING SATELLITE  
AND RADAR METEOROLOGY - 11

G. DUGDALE  
Dept. of Meteorology  
Univ. of Reading  
U.K.

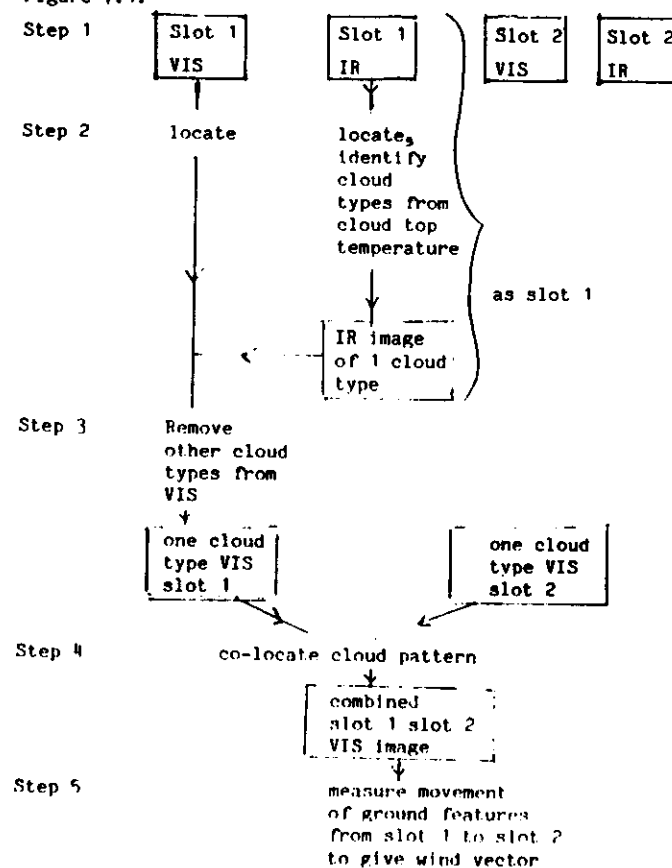
## 7 - FURTHER APPLICATIONS OF SATELLITE DATA IN METEOROLOGY

### 7.1 Wind finding

#### 7.1.1. Tropospheric winds

Over the oceans the tracking of clouds in either or both the visible and thermal infra-red channels offers a ready means of assessing wind speeds. It is assumed that the clouds are moved by the wind at about the level of their tops. This level is determined from the cloud top temperature and climatic or synoptic data about the atmospheric temperature profile. Many schemes involving automated or manual pattern recognition techniques have been developed for calculating satellite cloud tracking, most involve interactive image processing. A fairly typical method is outlined below.

Figure 7.1.



Steps 3 to 5 are repeated for each cloud level present.

Areas of about  $10^6$  square are treated at a time. Low level winds from stratocumulus or cumulus cloud movement have standard errors of about  $1.5 \text{ m s}^{-1}$  while high level winds from cirrus tracking give errors of about  $2.0 \text{ m s}^{-1}$ .

#### 7.1.2. Surface wind

Satellite borne radar has been used in an experimental mode to measure surface winds over the ocean. The SEASAT-A scatterometer system (SASS) detects the small scale roughness of the ocean surface from the increased radar back scattering, the change in polarization and the doppler shift of the back scattered signal indicate the direction of the wind relative to the satellite. The surface roughness is correlated with the wind speed empirically. Results indicate that winds may be measured to  $\pm 2.0 \text{ m s}^{-1}$  in strength and to  $\pm 20^\circ$  in direction.

### 7.2 Rainfall estimation from satellite data

#### 7.2.1. Microwave techniques

The most promising technique for rainfall estimation is the, as yet experimental, one using microwave emission to detect the presence of liquid water in clouds.

#### 7.2.2. Infra-red and visible techniques

As there is at present no commitment for operational meteorological satellites with microwave channels suitable for rainfall estimation.

Methods using the currently available visible and thermal infra-red channels have been developed experimentally and have had limited operational use.

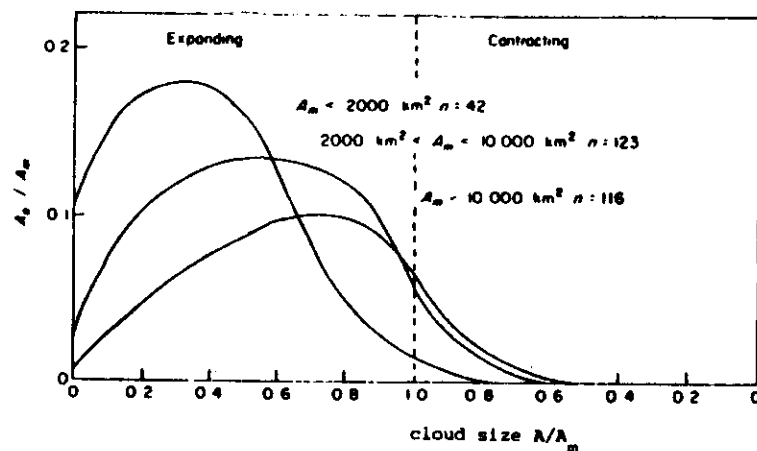
These methods rely on recognising the thermal I-R and VIS imagery the main characteristics of rain producing cloud systems. Large liquid water content gives rise to high reflectance in the visible channel and clouds reaching high levels in the atmosphere such as cumulonimbus can be recognised in the thermal I.R.

Figures 7.2. a, b, and c below illustrate these characteristics.

Fig. 7.2. Instantaneous brightness temperature and infrared data for a  $400 \times 400 \text{ km}$  box centred at  $00^\circ \text{N}$ ,  $10^\circ \text{W}$  in the eastern tropical Atlantic Ocean, 1300 GMT 5 September 1981. Data have been normalized to a scale 0-1. (a) No rain (b) 0-1 mm (c) 1-2 mm (d) 2-3 mm (e) 3-4 mm (f) 4-5 mm (g) 5-6 mm (h) 6-7 mm (i) 7-8 mm (j) 8-9 mm (k) 9-10 mm (l) 10-11 mm (m) 11-12 mm (n) 12-13 mm (o) 13-14 mm (p) 14-15 mm (q) 15-16 mm (r) 16-17 mm (s) 17-18 mm (t) 18-19 mm (u) 19-20 mm (v) 20-21 mm (w) 21-22 mm (x) 22-23 mm (y) 23-24 mm (z) 24-25 mm (aa) 25-26 mm (ab) 26-27 mm (ac) 27-28 mm (ad) 28-29 mm (ae) 29-30 mm (af) 30-31 mm (ag) 31-32 mm (ah) 32-33 mm (ai) 33-34 mm (aj) 34-35 mm (ak) 35-36 mm (al) 36-37 mm (am) 37-38 mm (an) 38-39 mm (ao) 39-40 mm (ap) 40-41 mm (aq) 41-42 mm (ar) 42-43 mm (as) 43-44 mm (at) 44-45 mm (au) 45-46 mm (av) 46-47 mm (aw) 47-48 mm (ax) 48-49 mm (ay) 49-50 mm (az) 50-51 mm (ba) 51-52 mm (bb) 52-53 mm (bc) 53-54 mm (bd) 54-55 mm (be) 55-56 mm (bf) 56-57 mm (bg) 57-58 mm (bh) 58-59 mm (bi) 59-60 mm (bj) 60-61 mm (bk) 61-62 mm (bl) 62-63 mm (bm) 63-64 mm (bn) 64-65 mm (bo) 65-66 mm (bp) 66-67 mm (bq) 67-68 mm (br) 68-69 mm (bs) 69-70 mm (bt) 70-71 mm (bu) 71-72 mm (bv) 72-73 mm (bw) 73-74 mm (bx) 74-75 mm (by) 75-76 mm (bz) 76-77 mm (ca) 77-78 mm (cb) 78-79 mm (cc) 79-80 mm (cd) 80-81 mm (ce) 81-82 mm (cf) 82-83 mm (cg) 83-84 mm (ch) 84-85 mm (ci) 85-86 mm (cj) 86-87 mm (ck) 87-88 mm (cl) 88-89 mm (cm) 89-90 mm (cn) 90-91 mm (co) 91-92 mm (cp) 92-93 mm (cq) 93-94 mm (cr) 94-95 mm (cs) 95-96 mm (ct) 96-97 mm (cu) 97-98 mm (cv) 98-99 mm (cw) 99-100 mm (cx) 100-101 mm (cy) 101-102 mm (cz) 102-103 mm (da) 103-104 mm (db) 104-105 mm (dc) 105-106 mm (dd) 106-107 mm (de) 107-108 mm (df) 108-109 mm (dg) 109-110 mm (dh) 110-111 mm (di) 111-112 mm (dj) 112-113 mm (dk) 113-114 mm (dl) 114-115 mm (dm) 115-116 mm (dn) 116-117 mm (do) 117-118 mm (dp) 118-119 mm (dq) 119-120 mm (dr) 120-121 mm (ds) 121-122 mm (dt) 122-123 mm (du) 123-124 mm (dv) 124-125 mm (dw) 125-126 mm (dx) 126-127 mm (dy) 127-128 mm (dz) 128-129 mm (ea) 129-130 mm (eb) 130-131 mm (ec) 131-132 mm (ed) 132-133 mm (ee) 133-134 mm (ef) 134-135 mm (eg) 135-136 mm (eh) 136-137 mm (ei) 137-138 mm (ej) 138-139 mm (ek) 139-140 mm (el) 140-141 mm (em) 141-142 mm (en) 142-143 mm (eo) 143-144 mm (ep) 144-145 mm (eq) 145-146 mm (er) 146-147 mm (es) 147-148 mm (et) 148-149 mm (eu) 149-150 mm (ev) 150-151 mm (ew) 151-152 mm (ex) 152-153 mm (ey) 153-154 mm (ez) 154-155 mm (fa) 155-156 mm (fb) 156-157 mm (fc) 157-158 mm (fd) 158-159 mm (fe) 159-160 mm (ff) 160-161 mm (fg) 161-162 mm (fh) 162-163 mm (fi) 163-164 mm (fj) 164-165 mm (fk) 165-166 mm (fl) 166-167 mm (fm) 167-168 mm (fn) 168-169 mm (fo) 169-170 mm (fp) 170-171 mm (fq) 171-172 mm (fr) 172-173 mm (fs) 173-174 mm (ft) 174-175 mm (fu) 175-176 mm (fv) 176-177 mm (fw) 177-178 mm (fx) 178-179 mm (fy) 179-180 mm (gz) 180-181 mm (ga) 181-182 mm (gb) 182-183 mm (gc) 183-184 mm (gd) 184-185 mm (ge) 185-186 mm (gf) 186-187 mm (gg) 187-188 mm (gh) 188-189 mm (gi) 189-190 mm (gj) 190-191 mm (gk) 191-192 mm (gl) 192-193 mm (gm) 193-194 mm (gn) 194-195 mm (go) 195-196 mm (gp) 196-197 mm (gq) 197-198 mm (gr) 198-199 mm (gs) 199-200 mm (gt) 200-201 mm (gu) 201-202 mm (gv) 202-203 mm (gw) 203-204 mm (gx) 204-205 mm (gy) 205-206 mm (gz) 206-207 mm (ha) 207-208 mm (hb) 208-209 mm (hc) 209-210 mm (hd) 210-211 mm (he) 211-212 mm (hf) 212-213 mm (hg) 213-214 mm (hh) 214-215 mm (hi) 215-216 mm (hj) 216-217 mm (hk) 217-218 mm (hl) 218-219 mm (hm) 219-220 mm (hn) 220-221 mm (ho) 221-222 mm (hp) 222-223 mm (hq) 223-224 mm (hr) 224-225 mm (hs) 225-226 mm (ht) 226-227 mm (hu) 227-228 mm (hv) 228-229 mm (hw) 229-230 mm (hx) 230-231 mm (hy) 231-232 mm (hz) 232-233 mm (ia) 233-234 mm (ib) 234-235 mm (ic) 235-236 mm (id) 236-237 mm (ie) 237-238 mm (if) 238-239 mm (ig) 239-240 mm (ih) 240-241 mm (ii) 241-242 mm (ij) 242-243 mm (ik) 243-244 mm (il) 244-245 mm (im) 245-246 mm (in) 246-247 mm (io) 247-248 mm (ip) 248-249 mm (iq) 249-250 mm (ir) 250-251 mm (is) 251-252 mm (it) 252-253 mm (iu) 253-254 mm (iv) 254-255 mm (iw) 255-256 mm (ix) 256-257 mm (iy) 257-258 mm (iz) 258-259 mm (ja) 259-260 mm (jb) 260-261 mm (jc) 261-262 mm (jd) 262-263 mm (je) 263-264 mm (jf) 264-265 mm (jg) 265-266 mm (jh) 266-267 mm (ji) 267-268 mm (jj) 268-269 mm (jk) 269-270 mm (jl) 270-271 mm (jm) 271-272 mm (jn) 272-273 mm (jo) 273-274 mm (jp) 274-275 mm (jq) 275-276 mm (jr) 276-277 mm (js) 277-278 mm (jt) 278-279 mm (ju) 279-280 mm (jv) 280-281 mm (jw) 281-282 mm (jx) 282-283 mm (jy) 283-284 mm (jz) 284-285 mm (ka) 285-286 mm (kb) 286-287 mm (kc) 287-288 mm (kd) 288-289 mm (ke) 289-290 mm (kf) 290-291 mm (kg) 291-292 mm (kh) 292-293 mm (ki) 293-294 mm (kj) 294-295 mm (kk) 295-296 mm (kl) 296-297 mm (km) 297-298 mm (kn) 298-299 mm (ko) 299-300 mm (kp) 300-301 mm (kq) 301-302 mm (kr) 302-303 mm (ks) 303-304 mm (kt) 304-305 mm (ku) 305-306 mm (kv) 306-307 mm (kw) 307-308 mm (kx) 308-309 mm (ky) 309-310 mm (kz) 310-311 mm (la) 311-312 mm (lb) 312-313 mm (lc) 313-314 mm (ld) 314-315 mm (le) 315-316 mm (lf) 316-317 mm (lg) 317-318 mm (lh) 318-319 mm (li) 319-320 mm (lj) 320-321 mm (lk) 321-322 mm (ll) 322-323 mm (lm) 323-324 mm (ln) 324-325 mm (lo) 325-326 mm (lp) 326-327 mm (lq) 327-328 mm (lr) 328-329 mm (ls) 329-330 mm (lt) 330-331 mm (lu) 331-332 mm (lv) 332-333 mm (lw) 333-334 mm (lx) 334-335 mm (ly) 335-336 mm (lz) 336-337 mm (ma) 337-338 mm (mb) 338-339 mm (mc) 339-340 mm (md) 340-341 mm (me) 341-342 mm (mf) 342-343 mm (mg) 343-344 mm (mh) 344-345 mm (mi) 345-346 mm (mj) 346-347 mm (mk) 347-348 mm (ml) 348-349 mm (mn) 349-350 mm (mo) 350-351 mm (mp) 351-352 mm (mq) 352-353 mm (mr) 353-354 mm (ms) 354-355 mm (mt) 355-356 mm (mu) 356-357 mm (mv) 357-358 mm (mw) 358-359 mm (mx) 359-360 mm (my) 360-361 mm (mz) 361-362 mm (na) 362-363 mm (nb) 363-364 mm (nc) 364-365 mm (nd) 365-366 mm (ne) 366-367 mm (nf) 367-368 mm (ng) 368-369 mm (nh) 369-370 mm (ni) 370-371 mm (nj) 371-372 mm (nk) 372-373 mm (nl) 373-374 mm (nm) 374-375 mm (no) 375-376 mm (np) 376-377 mm (nq) 377-378 mm (nr) 378-379 mm (ns) 379-380 mm (nt) 380-381 mm (nu) 381-382 mm (nv) 382-383 mm (nw) 383-384 mm (nx) 384-385 mm (ny) 385-386 mm (nz) 386-387 mm (oa) 387-388 mm (ob) 388-389 mm (oc) 389-390 mm (od) 390-391 mm (oe) 391-392 mm (of) 392-393 mm (og) 393-394 mm (oh) 394-395 mm (oi) 395-396 mm (oj) 396-397 mm (ok) 397-398 mm (ol) 398-399 mm (om) 399-400 mm (on) 400-401 mm (oo) 401-402 mm (op) 402-403 mm (oq) 403-404 mm (or) 404-405 mm (os) 405-406 mm (ot) 406-407 mm (ou) 407-408 mm (ov) 408-409 mm (ow) 409-410 mm (ox) 410-411 mm (oy) 411-412 mm (oz) 412-413 mm (pa) 413-414 mm (pb) 414-415 mm (pc) 415-416 mm (pd) 416-417 mm (pe) 417-418 mm (pf) 418-419 mm (pg) 419-420 mm (ph) 420-421 mm (pi) 421-422 mm (pj) 422-423 mm (pk) 423-424 mm (pl) 424-425 mm (pm) 425-426 mm (pn) 426-427 mm (po) 427-428 mm (pp) 428-429 mm (pq) 429-430 mm (pr) 430-431 mm (ps) 431-432 mm (pt) 432-433 mm (pu) 433-434 mm (pv) 434-435 mm (pw) 435-436 mm (px) 436-437 mm (py) 437-438 mm (pz) 438-439 mm (qa) 439-440 mm (qb) 440-441 mm (qc) 441-442 mm (qd) 442-443 mm (qe) 443-444 mm (qf) 444-445 mm (qg) 445-446 mm (qh) 446-447 mm (qi) 447-448 mm (qj) 448-449 mm (qk) 449-450 mm (ql) 450-451 mm (qm) 451-452 mm (qn) 452-453 mm (qo) 453-454 mm (qp) 454-455 mm (qq) 455-456 mm (qr) 456-457 mm (qs) 457-458 mm (qt) 458-459 mm (qu) 459-460 mm (qv) 460-461 mm (qw) 461-462 mm (qx) 462-463 mm (qy) 463-464 mm (qz) 464-465 mm (ra) 465-466 mm (rb) 466-467 mm (rc) 467-468 mm (rd) 468-469 mm (re) 469-470 mm (rf) 470-471 mm (rg) 471-472 mm (rh) 472-473 mm (ri) 473-474 mm (rj) 474-475 mm (rk) 475-476 mm (rl) 476-477 mm (rm) 477-478 mm (rn) 478-479 mm (ro) 479-480 mm (rp) 480-481 mm (rq) 481-482 mm (rr) 482-483 mm (rs) 483-484 mm (rt) 484-485 mm (ru) 485-486 mm (rv) 486-487 mm (rw) 487-488 mm (rx) 488-489 mm (ry) 489-490 mm (rz) 490-491 mm (sa) 491-492 mm (sb) 492-493 mm (sc) 493-494 mm (sd) 494-495 mm (se) 495-496 mm (sf) 496-497 mm (sg) 497-498 mm (sh) 498-499 mm (si) 499-500 mm (sj) 500-501 mm (sk) 501-502 mm (sl) 502-503 mm (sm) 503-504 mm (sn) 504-505 mm (so) 505-506 mm (sp) 506-507 mm (sq) 507-508 mm (sr) 508-509 mm (ss) 509-510 mm (st) 510-511 mm (su) 511-512 mm (sv) 512-513 mm (sw) 513-514 mm (sx) 514-515 mm (sy) 515-516 mm (sz) 516-517 mm (ta) 517-518 mm (tb) 518-519 mm (tc) 519-520 mm (td) 520-521 mm (te) 521-522 mm (tf) 522-523 mm (tg) 523-524 mm (th) 524-525 mm (ti) 525-526 mm (tj) 526-527 mm (tk) 527-528 mm (tl) 528-529 mm (tm) 529-530 mm (tn) 530-531 mm (to) 531-532 mm (tp) 532-533 mm (tq) 533-534 mm (tr) 534-535 mm (ts) 535-536 mm (tt) 536-537 mm (tu) 537-538 mm (tv) 538-539 mm (tw) 539-540 mm (tx) 540-541 mm (ty) 541-542 mm (tz) 542-543 mm (ua) 543-544 mm (ub) 544-545 mm (uc) 545-546 mm (ud) 546-547 mm (ue) 547-548 mm (uf) 548-549 mm (ug) 549-550 mm (uh) 550-551 mm (ui) 551-552 mm (uj) 552-553 mm (uk) 553-554 mm (ul) 554-555 mm (um) 555-556 mm (un) 556-557 mm (uo) 557-558 mm (up) 558-559 mm (uq) 559-560 mm (ur) 560-561 mm (us) 561-562 mm (ut) 562-563 mm (uu) 563-564 mm (uv) 564-565 mm (uw) 565-566 mm (ux) 566-567 mm (uy) 567-568 mm (uz) 568-569 mm (va) 569-570 mm (vb) 570-571 mm (vc) 571-572 mm (vd) 572-573 mm (ve) 573-574 mm (vf) 574-575 mm (vg) 575-576 mm (vh) 576-577 mm (vi) 577-578 mm (vj) 578-579 mm (vk) 579-580 mm (vl) 580-581 mm (vm) 581-582 mm (vn) 582-583 mm (vo) 583-584 mm (vp) 584-585 mm (vq) 585-586 mm (vr) 586-587 mm (vs) 587-588 mm (vt) 588-589 mm (vu) 589-590 mm (vv) 590-591 mm (vw) 591-592 mm (vx) 592-593 mm (vy) 593-594 mm (vz) 594-595 mm (wa) 595-596 mm (wb) 596-597 mm (wc) 597-598 mm (wd) 598-599 mm (we) 599-600 mm (wf) 600-601 mm (wg) 601-602 mm (wh) 602-603 mm (wi) 603-604 mm (wj) 604-605 mm (wk) 605-606 mm (wl) 606-607 mm (wm) 607-608 mm (wn) 608-609 mm (wo) 609-610 mm (wp) 610-611 mm (wq) 611-612 mm (wr) 612-613 mm (ws) 613-614 mm (wt) 614-615 mm (wu) 615-616 mm (wv) 616-617 mm (ww) 617-618 mm (wx) 618-619 mm (wy) 619-620 mm (wz) 620-621 mm (xa) 621-622 mm (xb) 622-623 mm (xc) 623-624 mm (xd) 624-625 mm (xe) 625-626 mm (xf) 626-627 mm (xg) 627-628 mm (xh) 628-629 mm (xi) 629-630 mm (xj) 630-631 mm (xk) 631-632 mm (xl) 632-633 mm (xm) 633-634 mm (xn) 634-635 mm (xo) 635-636 mm (xp) 636-637 mm (xq) 637-638 mm (xr) 638-639 mm (xs) 639-640 mm (xt) 640-641 mm (xu) 641-642 mm (xv) 642-643 mm (xw) 643-644 mm (xx) 644-645 mm (xy) 645-646 mm (xz) 646-647 mm (ya) 647-648 mm (yb) 648-649 mm (yc) 649-650 mm (yd) 650-651 mm (ye) 651-652 mm (yf) 652-653 mm (yg) 653-654 mm (yh) 654-655 mm (yi) 655-656 mm (yj) 656-657 mm (yk) 657-658 mm (yl) 658-659 mm (ym) 659-660 mm (yn) 660-661 mm (yo) 661-662 mm (yp) 662-663 mm (yq) 663-664 mm (yr) 664-665 mm (ys) 665-666 mm (yt) 666-667 mm (yu) 667-668 mm (yv) 668-669 mm (yw) 669-670 mm (yx) 670-671 mm (yy) 671-672 mm (yz) 672-673 mm (za) 673-674 mm (zb) 674-675 mm (zc) 675-676 mm (zd) 676-677 mm (ze) 677-678 mm (zf) 678-679 mm (zg) 679-680 mm (zh) 680-681 mm (zi) 681-682 mm (zj) 682-683 mm (zk) 683-684 mm (zl) 684-685 mm (zm) 685-686 mm (zn) 686-687 mm (zo) 687-688 mm (zp) 688-689 mm (zq) 689-690 mm (zr) 690-691 mm (zs) 691-692 mm (zt) 692-693 mm (zu) 693-694 mm (zv) 694-695 mm (zw) 695-696 mm (zx) 696-697 mm (zy) 697-698 mm (zz) 698-699 mm (aa) 699-700 mm (ab) 700-701 mm (ac) 701-702 mm (ad) 702-703 mm (ae) 703-704 mm (af) 704-705 mm (ag) 705-706 mm (ah) 706-707 mm (ai) 707-708 mm (aj) 708-709 mm (ak) 709-710 mm (al) 710-711 mm (am) 711-712 mm (an) 712-713 mm (ao) 713-714 mm (ap) 714-715 mm (aq) 715-716 mm (ar) 716-717 mm (as) 717-718 mm (at) 718-719 mm (au) 719-720 mm (av) 720-721 mm (aw) 721-722 mm (ax) 722-723 mm (ay) 723-724 mm (az) 724-725 mm (ba) 725-726 mm (bb) 726-727 mm (bc) 727-728 mm (bd) 728-729 mm (be) 729-730 mm (bf) 730-731 mm (bg) 731-732 mm (bh) 732-733 mm (bi) 733-734 mm (bj) 734-735 mm (bk) 735-736 mm (bl) 736-737 mm (bm) 737-738 mm (bn) 738-739 mm (bo) 739-740 mm (bp) 740-741 mm (bq) 741-742 mm (br) 742-743 mm (bs) 743-744 mm (bt) 744-745 mm (bu) 745-746 mm (bv) 746-747 mm (bw) 747-748 mm (bx) 748-749 mm (by) 749-750 mm (bz) 750-751 mm (ca) 751-752 mm (cb) 752-753 mm (cc) 753-754 mm (cd) 754-755 mm (ce) 755-756 mm (cf) 756-757 mm (cg) 757-758 mm (ch) 758-759 mm (ci) 759-760 mm (cj) 760-761 mm (ck) 761-762 mm (cl) 762-763 mm (cm) 763-764 mm (cn) 764-765 mm (co) 765-766 mm (cp) 766-767 mm (cq) 767-768 mm (cr) 768-769 mm (cs) 769-770 mm (ct) 770-771 mm (cu) 771-772 mm (cv) 772-773 mm (cw) 773-774 mm (cx) 774-775 mm (cy) 775-776 mm (cz) 776-777 mm (da) 777-778 mm (db) 778-779 mm (dc) 779-780 mm (dd) 780-781 mm (de) 781-782 mm (df) 782-783 mm (dg) 783-784 mm (dh) 784-785 mm (di) 785-786 mm (dj) 786-787 mm (dk) 787-788 mm (dl) 788-789 mm (dm) 789-790 mm (dn) 790-791 mm (do) 791-792 mm (dp) 792-793 mm (dq) 793-794 mm (dr) 794-795 mm (ds) 795-796 mm (dt) 796-797 mm (du) 797-798 mm (dv) 798-799 mm (dw) 799-800 mm (dx) 800-801 mm (dy) 801-802 mm (dz) 802-803 mm (ea) 803-804 mm (eb) 804-805 mm (ec) 805-806 mm (ed) 806-807 mm (ee) 807-808 mm (ef) 808-809 mm (eg) 809-810 mm (eh) 810-811 mm (ei) 811-812 mm (ej) 812-813 mm (ek) 813-814 mm (el) 814-815 mm (em) 815-816 mm (en) 816-817 mm (eo) 817-818 mm (ep) 818-819 mm (eq) 819-820 mm (er) 820-821 mm (es) 821-822 mm (et) 822-823 mm (eu) 823-824 mm (ev) 824-825 mm (ew) 825-826 mm (ex) 826-827 mm (ey) 827-828 mm (ez) 828-829 mm (fa) 829-830 mm (fb) 830-831 mm (fc) 831-832 mm (fd) 832-833 mm (fe) 833-834 mm (ff) 834-835 mm (fg) 835-836 mm (fh) 836-837 mm (fi) 837-838 mm (fj) 838-839 mm (fk) 839-840 mm (fl) 840-841 mm (fm) 841-842 mm (fn) 842-843 mm (fo) 843-844 mm (fp) 844-845 mm (fq) 845-846 mm (fr) 846-847 mm (fs) 847-848 mm (ft) 848-849 mm (fu) 849-850 mm (fv) 850-851 mm (fw) 851-852 mm (fx) 852-853 mm (fy) 853-854 mm (fz) 854-855 mm (ga) 855-856 mm (gb) 856-857 mm (gc) 857-858 mm (gd) 858-859 mm (ge) 859-860 mm (gf) 860-861 mm (gg) 861-862 mm (gh) 862-863 mm (gi) 863-864 mm (gj) 864-865 mm (gk) 865-866 mm (gl) 866-867 mm (gm) 867-868 mm (gn) 868-869 mm (go) 869-870 mm (gp) 870-871 mm (gq) 871-872 mm (gr) 872-873 mm (gs) 873-874 mm (gt) 874-875 mm (gu) 875-876 mm (gv) 876-877 mm (gw) 877-878 mm (gx) 878-879 mm (gy) 879-880 mm (gz) 880-881 mm (ha) 881-882 mm (hb) 882-883 mm (hc) 883-884 mm (hd) 884-885 mm (he) 885-886 mm (hf) 886-887 mm (hg) 887-888 mm (hh) 888-889 mm (hi) 889-890 mm (hj) 890-891 mm (hk) 891-892 mm (hl) 892-893 mm (hm) 893-894 mm (hn) 894-895 mm (ho) 895-896 mm (hp) 896-897 mm (hq) 897-898 mm (hr) 898-899 mm (hs) 899-900 mm (ht) 900-901 mm (hu) 901-902 mm (hv) 902-903 mm (hw) 903-904 mm (hx) 904-905 mm (hy) 905-906 mm (hz) 906-907 mm (ia) 907-908 mm (ib) 908-909 mm (ic) 909-910 mm (id) 910-911 mm (ie) 911-912 mm (if) 912-913 mm (ig) 913-914 mm (ih) 914-915 mm (ii) 915-916 mm (ij) 916-917 mm (ik) 917-918 mm (il) 918-919 mm (im) 919-920 mm (in) 920-921 mm (io) 921-922 mm (ip) 922-923 mm (iq) 923-924 mm (ir) 924-925 mm (is) 925-926 mm (it) 926-927 mm (iu) 927-928 mm (iv) 928-929 mm (iw) 929-930 mm (ix) 930-931 mm (iy) 931-932 mm (iz) 932-933 mm (ja) 933-934 mm (jb) 934-935 mm (jc) 935-936 mm (jd) 936-937 mm (je) 937-938 mm (jf) 938-939 mm (jg) 939-940 mm (jh) 940-941 mm (ji) 941-942 mm (jj) 942-943 mm (jk) 943-944 mm (jl) 944-945 mm (jm) 945-946 mm (jn) 946-947 mm (jo) 947-948 mm (jp) 948-949 mm (jq) 949-950 mm (jr) 950-951 mm (js) 951-952 mm (jt) 952-953 mm (ju) 953-954 mm (jv) 954-955 mm (jw) 955-956 mm (jx) 956-957 mm (jy) 957-958 mm (jz) 958-959 mm (ka) 959-960 mm (kb) 960-961 mm (kc) 961-962 mm (kd) 962-963 mm (

The interpretation of the clouds VIS and/or I.R. features in terms of rainfall has followed two principle lines. First, the use of high quality photographic type imagery to recognise typical rain bearing systems and to attribute rainfall amounts to them according to their persistence over an area and the climatologically expected rainfall from such systems. These methods have achieved some success particularly when used as interpolation schemes between raingauges and when applied to large scale synoptic rainfall events which give rise to relatively homogeneous rainfall at the ground. The second method, more suitable for convective rainfall, consists of monitoring the development of clouds using digital I-R data sometimes in conjunction with the visible data. It is found that convective systems give most of their rainfall in their growth stage and that having reached their maximum horizontal extent generally give little precipitation. Figure 7.3. below illustrates this.

Fig. 7.3. The area of rain producing cloud ( $A$ ) a function of the size of the cloud ( $A$ ). Both scales are normalized by the maximum size the cloud attains ( $A_m$ ). The curves represent clouds of three different size ranges. (after Barrett and Martin, 1981).



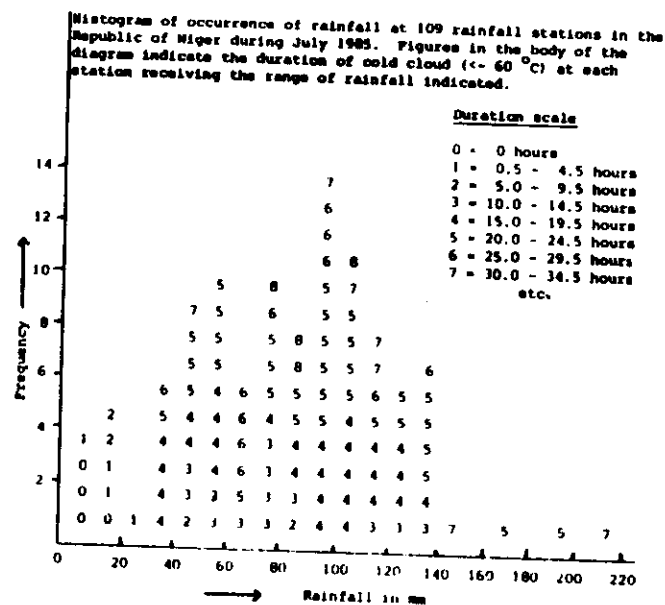
The implication of the above is that convective systems must be monitored each hour or so if reasonable estimates of rainfall from them are to be made. Hence, data from geostationary satellites must be used. Only the I-R channel can monitor their activity during the night. Most experimental and quasi-operational models employ a rainrate ( $R$ ) equation of the form:

$$R = a_0 + a_1 \frac{dA}{dt} + \text{additional terms}$$

where  $a_0$  implies the presence of cold cloud below a predetermined temperature (temperatures from 223 K to 243 K have been used) and  $\frac{dA}{dt}$  is the rate of growth of the area of cloud below that or another predetermined temperature. The additional terms may include such factors as storm propagation or decay. All these schemes are empirical and the coefficients established for one climatic region are not universally applicable; for instance those developed for convective storms over the tropical Atlantic Ocean proved inappropriate over continental West Africa.

Estimates of rainfall from tropical convective systems over long periods (30 days) or over large areas may be achieved without the inclusion of the growth term in the above equation. One is then left with the rainfall being related to the persistence of clouds of convective origin over a site or the mean fractional cover over an area. The implication is that, in the absence of geographic effects, when averaged over a number of rainfall events a site would experience some storms in each phase of growth or decay. Figure 7.4. shows a contingency table for the rainfall and persistence of cold cloud over sites in the Republic of Niger in

Figure 7.4.



In interpreting such diagrams it is necessary to recall the large spatial variability of rainfall from these storm systems. Typically rainfall from large systems will vary by a factor of two over distances of ten kilometers. Hence raingauge data can only be used in a statistical sense to calibrate satellite estimates and similarly a satellite estimate that gave an accurate mean rainfall over a 5 km x 5 km pixel would have to be interpreted in terms of a widely spread rainfall distribution within that pixel.

### 7.3. Soil moisture and evaporation measurement from satellite data

Techniques for the estimation of soil moisture and evaporation from satellite data are generally based on surface energy budget (SEB) concepts and involve the use of both satellite and surface data.

The SEB may be written

$$R_N = H + \lambda E + G$$

net radiation towards the surface = sensible heat flux from the surface + evaporative heat flux from the surface + ground heat flux from the surface

$$\text{with } R_N = S(1 - \alpha) + L_{\downarrow} - L_{\uparrow}$$

absorbed solar radiation = downwards long wave radiation - upwards long wave radiation

The solar radiative term may be estimated from the visible channel data using climatological data for the atmospheric absorption loss. The long wave radiative terms can be calculated from satellite measured atmospheric and surface temperatures. If clouds are present cloud base temperatures must be estimated.

The heat flux terms are usually expressed in resistance terminology

$$H = \rho C_p \frac{T_s - T_a}{r_a} ; \quad \lambda E = \rho \frac{C_p}{\gamma} \frac{(e_s - e_a)}{r_a}$$

$$G = k \frac{\partial T}{\partial z} \Big|_{z=0} \text{ with } C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \text{ in the soil}$$

where  $r_a$  is an aerodynamic resistance which depends on wind speed and vertical temperature gradient,  $k$  is the thermal conductivity of the soil and  $C$  its volumetric thermal capacity.  $C$  is slightly dependant on soil moisture content and  $k$  strongly dependant.

If surface synoptic data ( $T_a, e_a, u_a$ ) are available  $H$  may be calculated. The vapour pressure at the ground surface ( $e_s$ ) is not usually known but it may be related empirically to the saturated vapour pressure at the earth surface and the difference in temperature between the surface and the air. Another approach to the  $\lambda E$  term is to express it as

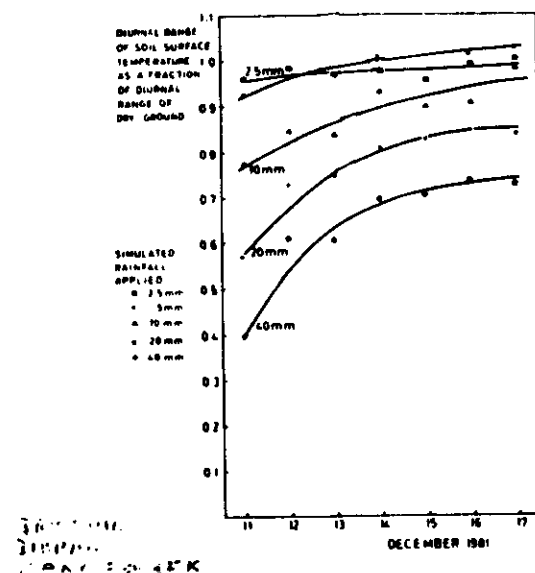
$$\lambda E = \rho \frac{C_p}{\gamma} \frac{(e_s - e_a)}{r_a + r_s}$$

where  $\delta$  is the depth below the soil surface at which water is available for evaporation,  $e_\delta$  is then the saturated water vapour pressure at the temperature corresponding to that depth. Models to solve these equations

using up to twentyfour data points per day have been developed. Other models assume all changes to be cyclic and use only two data points per day. Over bare soils with high insolation evaporation is controlled almost entirely by the resistance to vapour diffusion through the dry upper layer of soil. Under these conditions for a specified type of soil the diurnal range of surface temperature reflects well the depth of the dry layer and hence the availability of water for evaporation.

Figure 7.5 illustrates the effect on the diurnal range of temperature of a bare soil surface of irrigation and shows the rate of recovery of the temperature cycle towards the dry condition as water evaporates through the upper layers. This is the basis of one method for the estimation of soil moisture in the upper layers and of evaporation from satellite data.

FIG. 7.5.



There are at present at least six models being tested for evaporation and soil moisture monitoring but none appear to have yet reached an operationally viable state.

## 10 - SOME OTHER APPLICATIONS OF RADAR

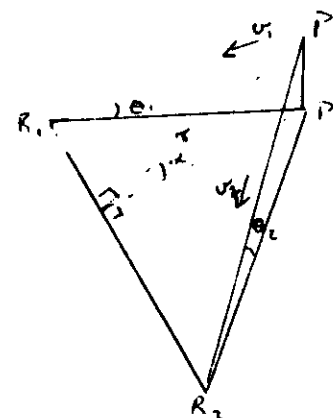
There are many examples of the use of radar in cloud physics and turbulence research. In this section two examples of research with radar are given. They are chosen because of the interesting novel techniques which are applied.

### 10.1 Radar wind finding in convective storms

Wind fields in clouds are very difficult to determine unless some components of the cloud itself can be used as tracers. Various methods, using two or more doppler radars, have been devised to investigate circulation patterns in storms. One using the "COPLAN" technique is given below.

Two doppler radars on a base line fifty to one hundred kilometers long are used to view the same section of a storm simultaneously and the velocity of the raindrops towards each radar is determined from the doppler shift.

The geometry is illustrated below



$R_1, R_2$  radars

P section of cloud being observed

$P'$  plan position of P

$\theta_1, \theta_2$  elevations of P from  $R_1, R_2$

$v_1, v_2$  doppler velocities towards  $R_1, R_2$

$r$  the radial distance from P to  $R_1, R_2$  making  $\alpha$  to the horizontal

The doppler velocities  $U_1, U_2$  contain a component from the fall speed of the drops. This may be deduced from empirical relationships between  $Z$  and the terminal velocity. One such after Atlas et al (1973) is

$$w = 2.65 Z^{0.114} (\rho/\rho_0)^{0.4} \text{ m s}^{-1} \text{ where}$$

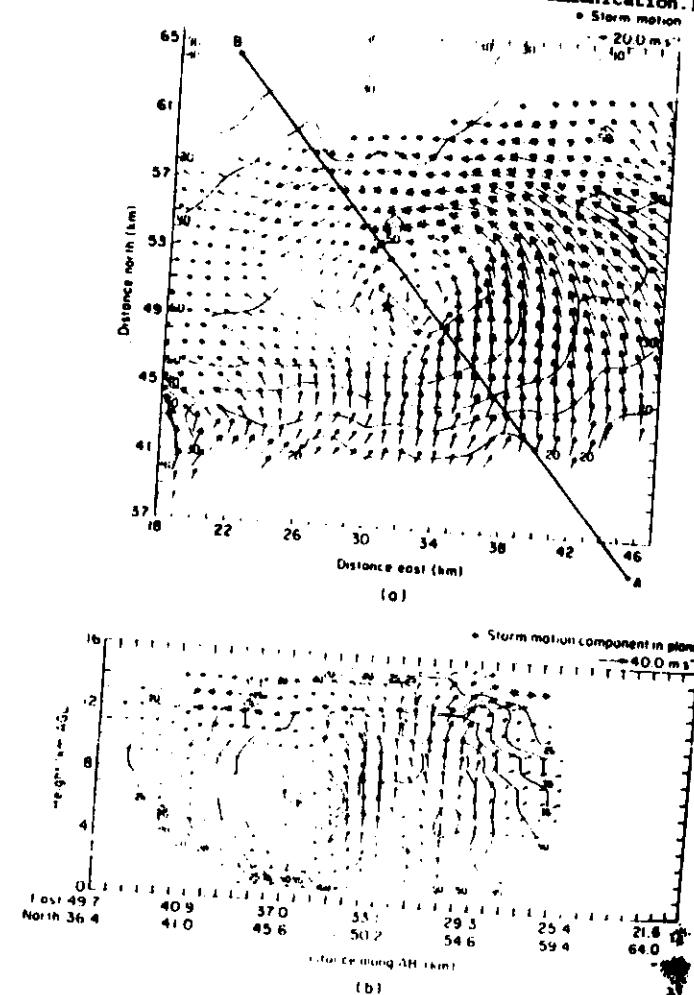
$w$  is the population mean terminal velocity and  $\rho$

is air density. The doppler velocities are adjusted to  $U_1, U_2$  where  $U_1 = U + w \sin \theta$   
From  $U_1, U_2$  two components of the air velocity at  $P$  in the plane

$r, R_1 R_2$ . For ease of computation the components along and perpendicular to  $r$  are used. A series of wind fields are measured in planes containing  $R_1 R_2$ . The equation of continuity in a cylindrical co-ordinate system is then used to establish the three dimensional wind field which is then transformed to more conventional horizontal and vertical co-ordinates. Boundary conditions are zero vertical component at the tropopause and ground surface.

The result of a storm study by Brandes and Johnson\* using these methods is illustrated in Figure 10.1

Figure 10.1. (a) Contours of reflectivity factor (in dBZ) and the storm relative wind field in a horizontal cross section at 2 km above ground level and (c) a vertical cross section of a tornadic thunderstorm on 2 May 1979, at 16:58 C.S.T. Winds are in the coordinate system moving with the storm. Storm motion speed and direction are shown. Line AB in (a) is the location of the vertical cross section. Distances are from a radar at Roman Nose State Park, Oklahoma (Alberty et al., 1979). The star pinpoints the tornado location in (a). The arrow of indicated velocity at the top right of each plot gives the speed which is proportional to the arrow's length. (From E. Brandes and N. Johnson, NSSL, personal communication.)



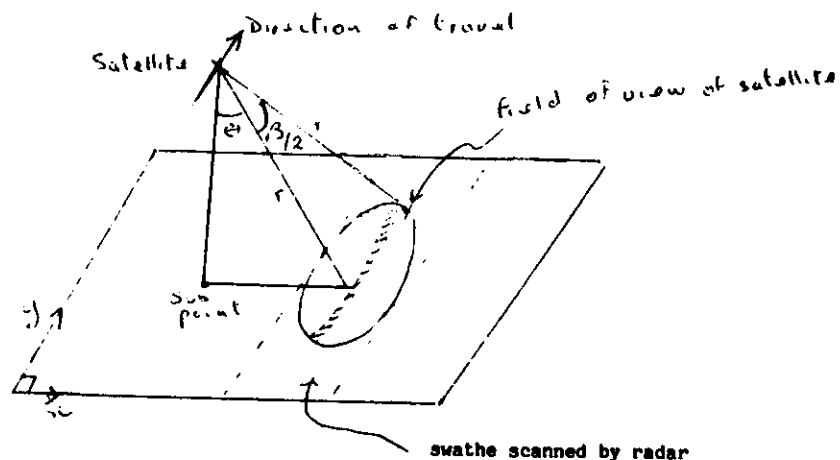
\* Reported by Douiak and Zrnic (1984), Doppler Radar and Weather Observations, Academic Press.

## 10.2 Radar on satellites

Two problems of satellite borne radar arise from the large distances between the radar and the target. The maximum resolution  $\left(\frac{1.22 \lambda}{D}\right)$  means that for a satellite even with a ten metre antenna the ground resolution would be of the order of 10 km for a satellite orbiting at 1000 km and several hundred kilometers for a geostationary satellite. The second difficulty is that of the return power available. With an orbiting satellite the received power is only about  $10^{-23}$  of the transmitted power which is itself much lower than the power transmitted from ground based radar.

Interesting solutions to these difficulties were found on the Synthetic Aperture Radar (SAR).

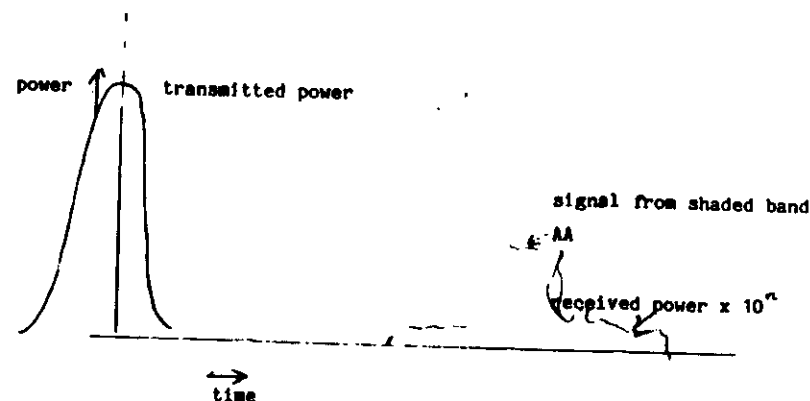
This radar viewed the earth's surface obliquely at right angles to the direction of travel of the satellite.



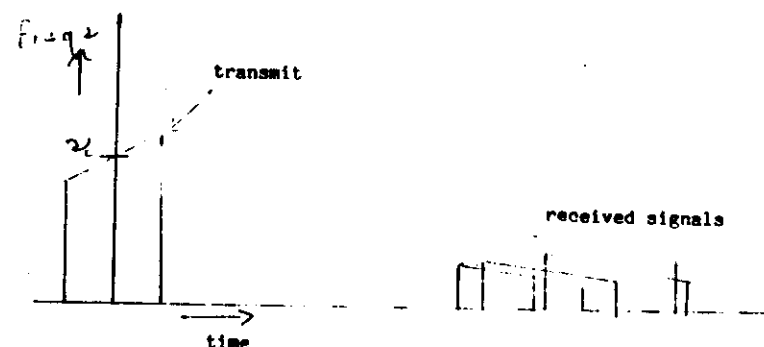
Resolution in the x direction depends on  $\theta$  and on the pulse length, and equals  $\left(\frac{\text{pulse length}}{2 \cos \theta}\right)$ . In the y direction the resolution is  $r \sin \beta$ .

For many purposes neither the x nor the y resolution as described above are adequate.

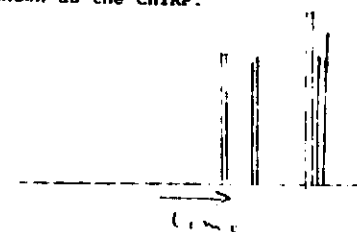
When a pulse is transmitted and received its power/time curve may resemble



In the SAR both the received power and the x direction resolution are increased by coding the pulse signal by changing its frequency slightly throughout the duration of the pulse.

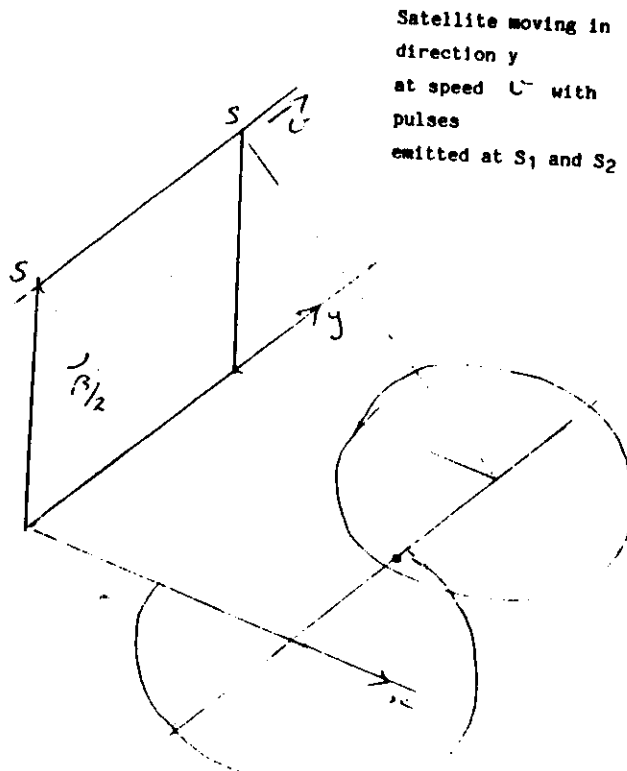


The received signal is then delayed according to its frequency so the whole pulse is compressed after reception, thus increasing power and resolution. This technique is known as the CHIRP.



The synthetic aperture method increases the y resolution. The principle is that if a series of identical pulses and echoes are emitted and received by a moving antenna it is possible to recombine the received data as though all the pulses had been emitted simultaneously by a large antenna. The limit of the principle is that any surface point must receive at least two pulses. Hence we have the paradox that the smaller the actual antenna the larger in principle is the resolving power of the synthetic aperture. In fact power considerations give a lower limit to the antenna size. The higher the pulse repetition frequency (P.R.F.) the more pulses will give information on any one point but the P.R.F. must not be so high that back scatter from two sources could be confused.

A simple analysis of the geometry of the SAR principle is given below.



The size of the synthetic aperture ( $A_s$ ) may be considered to be the size of the "footprint" in the y direction =  $r/\beta$

$$\text{with } \beta = \frac{1.22 \lambda}{A_r}$$

where  $A_r$  is the effective aperture of the actual antenna

$$\text{So } A_s = \frac{1.22 \lambda r}{A_r}$$

and the angular resolution  $\beta_s$  of the synthetic aperture is given by

$$\beta_s = \frac{1.22 \lambda A_r}{1.22 \lambda r} = \frac{A_r}{r}$$

and the linear resolution is  $\Delta p$ .

This is perhaps more easily seen if one considers that the only unique information about the position of a point in the y direction is its doppler shift. The maximum doppler shift is given by

$$\Delta f = 2 \frac{v}{c} f_0$$

and for two close points the maximum difference in frequencies of the return signal is given by

$$\Delta F = 2 \frac{v}{c} \frac{\Delta p}{r} f_0$$

where  $\Delta p$  is the y separation of the points

if  $\Delta p$  is the minimum resolvable distance the angular resolution is

$$\begin{aligned} \Delta p &= \frac{r \Delta F c}{2 v f_0} \\ &= r \frac{\Delta F \lambda_0}{c} \\ &= \frac{T \Delta F \lambda_0}{\beta} \end{aligned}$$

$$\approx T \Delta F A_r$$

where T is the time during which a point remains in view of the satellite

but the minimum resolvable frequency is  $1/T$  so the linear resolution is  $A_r$ . The pulse repetition frequency limits are that a point must remain



In view for more than two pulses

$$\text{i.e. min P.R.F.} > \frac{U}{A_r}$$

$$\text{Also for signals to be unambiguous the P.R.F.} < \frac{C}{2r}$$

