Annu. Rev. Astron. Astrophys. 1999. 37:65–96

FREQUENCY ALLOCATION: The First Forty Years

Brian Robinson
Research Fellow Emeritus, Australia Telescope National Facility, Epping, N.S.W. 2121 Australia; e-mail: brobinso@ozemail.com.au

Key Words Frequency management, IUCAF, world radio conferences, radio interference, mobile satellites, radio astronomy

■ **Abstract** In 1960 ICSU set up an Inter-Union Commission (IUCAF) on the Allocation of Frequencies for Space Research and Radio Astronomy, to keep key parts of the radio spectrum clear for passive, scientific use. IUCAF represents URSI, IAU and COSPAR at World Radio Conferences (WRCs) convened by the International Telecommunications Union (ITU) in Geneva; the WRCs establish the international law which governs users of the radio spectrum. This review recounts many serious threats posed to passive scientific research by commercial and military operations, particularly those involving radio emissions from aircraft and spacecraft. The continual conflict between commercial greed and scientific curiosity has often put the future of radio astronomy, space research, and earth exploration in jeopardy. The conflict increases as we move into the Information Age.

1. THE BEGINNINGS: 1952–1959

This review recounts the role of the Inter-Union Commission on the Allocation of Frequencies (IUCAF), and its predecessor in the International Scientific Radio Union (URSI), to keep some parts of the radio spectrum clear for passive, scientific use. IUCAF is responsible for protecting the frequencies needed by radio astronomy, space research, and environmental monitoring of the Earth. The 40-year struggle has a parallel in the continuing fight of astronomers to keep some sky dark, despite street lights, advertising, aircraft, spacecraft, and recurrent ideas for space advertising.

1.1 Interference

In the late nineteenth century, attempts to detect radio waves from extraterrestrial sources were made by Ebert, Jansen, Lodge, and others. Lodge found that a sensitive coherer was subject to "too many terrestrial sources of disturbance in a city like Liverpool to make the experiment feasible" (Smith 1960). So there has been awareness of "terrestrial sources of disturbance" since the earliest experiments.

0066-4146/99/0915-0065$08.00

Interference played a major part in Karl Jansky's 1932 discovery of radio waves from the galaxy. It was a result of his investigation, for Bell Telephone Labs, of the sources of interference experienced on 20.5 MHz radio links, using a directional antenna to scan in azimuth. The arrival of one type of interference advanced by four minutes each day, which Jansky identified as a sidereal rate (Jansky 1979).

1.2 World War II: New Technology

Between 1932 and World War II, radio astronomy had been an individual, amateur effort: Grote Reber was building receivers and a steerable dish in the backyard of his house in Wheaton, Illinois.

The development of radar in the United Kingdom from 1935, and the enormous growth of radar and communications technology from 1939 to 1945 trained many people in microwave techniques and gave them advanced hardware. During the war J.S. Hey had identified radiation from a sunspot, and observed emission from Cygnus A and radio reflections from meteor trails.

The scene was set for great expansion of radio astronomy after the war, and radio observatories began at Sydney and Cambridge. The Radiophysics Laboratory in Sydney had been the center for radar development in the South Pacific, and when the war ended the group remained intact, looking for other applications of the new radio technology.

Martin Ryle had been involved in British radar research and development, particularly countermeasures in aircraft. At the end of the war Ryle was put in a major's uniform and sent to Germany to steal Nazi technology. Ryle came back to England with airborne radar equipment and two Wurzburg radar antennas, which Ryle, Graham Smith, and Bruce Elsmore set up as an interferometer at Cambridge. Other important groups formed in Europe: Jodrell Bank, Leiden, Meudon, Onsala, and others. Wurzburg antennas appeared everywhere. In the United States work began at Harvard University and the Naval Research Laboratories, located in Washington, D.C., to follow up the early work at Sydney and Cambridge.

However, the amazing growth of technology during the war equally set the stage for remarkable developments in radio communications, broadcasting, and navigation, both civil and military. The potential for interference to radio astronomy from radar and communications was unavoidable. In the last forty years we have seen a burgeoning use of the radio spectrum for every conceivable purpose. Conflict arose between those who want to transmit and those who want to listen to emissions from space—understandably so because the emissions from space are, to traditional communications engineers, unbelievably weak.

1.3 International Cooperation in Radio Astronomy

From the time of the 1905 Berlin Conference, there had been many international efforts to carve up the radio spectrum between different users. The International Telecommunications Union (ITU) was born in 1919, as a branch of the League of Nations, to wield the carving knife. In 1959 the ITU (now a United Nations body) called a World Conference to re-allocate the radio spectrum and to allocate bandwidths that were inaccessible at the time of the 1937 ITU World Conference in Cairo but became accessible with technology that was brand new at the time of the 1947 Atlantic City World Conference.

Radio astronomers were quick to prepare for and take part in the 1959 World Conference in Geneva. Radio astronomy observations of "radio sources" had already been carried out at frequencies from 18 MHz (Shain 1951) to 24 GHz (Piddington and Minnett 1949). In 1951 the first radio spectral line, atomic hydrogen, had been discovered from the Milky Way at 1420.405 MHz (Ewen & Purcell 1951).

The ITU has a technical arm that was then known as Comite Consultatif International des Radiocommunications (CCIR). Recommendations from CCIR study groups carried great weight at ITU world conferences. Balth van der Pol from Holland played an important part in CCIR as director from 1949 to 1957, as did F.L.H.M. Stumpers, R.L. Smith-Rose and Fred Horner from the United Kingdom, and John P. Hagen from the United States. From 1953 important work was done in London by a CCIR study group responsible for radio astronomy. A history of the CCIR from 1929 to 1989 can be found in Kirby (1978, 1989) and Stumpers (1989). Kirby and Struzak (1994) give a retrospect on the CCIR view on frequency allocations for radio astronomy.

Union Radio Scientifique Internationale Radio astronomy had found an international home in URSI as Commission V. The new commission was founded in 1948 with the title "Extraterrestrial Radio Noise." By the time of its first meeting at the 1950 URSI General Assembly in Zurich, the title of Commission V had been changed to "Radio Astronomy." At the first session, on September 13, 1950, the death of Karl Jansky in February was announced. Commission V next met in Sydney in 1952, in The Hague in 1954, and in Boulder in 1957.

CCIR met in Warsaw in 1956 and drew up Recommendation No. 173 on Protection of Frequencies Used for Radio Astronomical Measurements (Smith-Rose 1956). "Rec. 173" was referred to Commission V of URSI, and the 1957 General Assembly of URSI in Boulder set up Sub-Commission Ve on Frequency Allocation, charged with protection of the radio spectrum for radio astronomy and preparing recommendations to be submitted to the ITU. The initial membership (Haddock 1957) was F.T. Haddock (Chair), E.J. Blum, A. Hewish, V.V. Vitkevitch, W.N. Christiansen, A.H. de Voogt, T. Hatanaka, L. Erikson, F. Becker, A.E. Covington, G. Righini, J. Tuominen, O.E.H. Rydbeck, R. Coutrez and A.P. Mitra.

Sub-Commission Ve under F. T. Haddock, then J.W. Findlay (from 1958), took part in the submissions made by CCIR (at its Plenary in Los Angeles in April 1959) to the 1959 ITU World Conference. Activity by national governments was also required—the ITU is a United Nations body, and only U.N. member countries can vote on proposals. The involvement of governments is crucial because delegates from URSI and IUCAF can speak at conference sessions, but never vote.

The World Conference lasted for three months, and the case for radio astronomy was supported in rotation by J.H. Oort (IAU President), B. van der Pol, H.C. van de Hulst, J.F. Denisse, J.W. Findlay, C.L. Seeger, R. Coutrez and W.J.G. Beynon. Van der Pol, the strong supporter of science, died in October. Oort (1960) published a special public lecture given at WARC-1959.

The main burden at the WARC fell on Charles Seeger (secretary of URSI Sub-Commission Ve). John Findlay (1988) describes the support of The Netherlands and the United Kingdom, and the opposition of the United States (Sullivan 1959, Lear 1959, Finney 1959). Seeger tells of later charges against him of "un-American activities;" being the brother of folk singer Pete Seeger didn't help his position.

Although falling considerably below the hopes of radio astronomers, WARC-1959 laid a good basis for radio astronomy, notably the exclusive "passive" band at 1400–1427 MHz for 21 cm hydrogen line observations. In 1959 there was little commercial or military demand for frequencies above 1000 MHz, and allocations (in footnote form) of reasonable bandwidth were possible. There was less success with the request for allocations of a 2.5 percent band every octave in frequency for continuum observations.

The ITU recognizes radio services, such as broadcasting, fixed networks, radionavigation, radar, mobile communications, amateur use, and meteorological aids. A major victory at the World Conference in 1959 was to have the ITU accept the idea of a "passive service." Until that point, a service had to transmit radio waves; those who only received signals had been a totally different group, outside the ambit of the ITU.

The WARC agreed that the needs of radio astronomy and space science would be included in a "Space" WARC to be held in 1963.

In his report to URSI, Findlay (1960) recommended that Sub-Commission Ve be dissolved, to be replaced by a group representing URSI, IAU, and COSPAR. But Sub-Commission Ve continued until the 1966 URSI General Assembly in Munich.

As well as Commission V in URSI, radio astronomy had also found a place as Commission 40 in the International Astronomical Union. This Commission Pour les Observations Radioelectriques did not meet at the Rome IAU General Assembly in 1952, but its president sent a report to the IAU Transactions (Woolley 1952). By the 1955 General Assembly of IAU in Dublin, Commission 40 had its first meeting, with the title Commission de Radio-Astronomie. Appendix I of the Proceedings (Pawsey 1955) addressed the general requirements for frequency allocations (proposed by Laffineur, Hagen, de Voogt, Ryle, and Vitkevitch).

The last IAU General Assembly before WARC-1959 was the 1958 meeting in Moscow, which re-affirmed the broad requirements for protection of radio astronomy. At the following IAU General Assembly (Berkeley 1961) J-F. Denisse (1961) reported that *CCIR (Los Angeles 1958) a enterine dans ses grandes lignes les demandes d'allocation de frequences formulees par l'UAI à Moscou* [which translates to English as, "CCIR (Los Angeles 1958) ratified in the main proposals for frequency allocations formulated by the IAU in Moscow"].

2. THE FORMATION OF IUCAF: 1960 to 1971

By 1960 two significant developments occurred: the formation of COSPAR, and the proposal from the MIT Lincoln Laboratory for Project WEST FORD (the Needles Project, funded by the U.S. Air Force). They proposed a reflective belt of dipoles in a circular orbit around the Earth at a height of 3000 kilometers. The orbital scatter concept was proposed by W.E. Morrow (of Lincoln Lab) in 1958 in collaboration with H. Meyer (of Thompson Ramo Wooldridge Inc.).

2.1 IUCAF: London 1960

Project WEST FORD presented a great threat to radio astronomy, optical astronomy, and space research, and called for a combined response by URSI, IAU, and COSPAR. An ICSU Inter-Union Commission was set up by URSI's Executive Committee on September 2, 1960, encouraged by Lloyd Berkner. The members initially appointed were J.A. Ratcliffe (Chair), R. Emberson, L.G.H. Huxley (on behalf of COSPAR), V. Ilyin and H. Sterky.

At their first meeting in London on September 5, 1960, Ratcliffe suggested that coordination of activities with Commission V of URSI would be achieved if J.W. Findlay were to be co-opted to the committee as its secretary. Findlay attended the second meeting on September 8, 1960, presented the report of Sub-Commission Ve (Findlay 1960) and outlined the work that had been done in getting protected frequencies for radio astronomy during 1958 and 1959.

IUCAF's Terms of Reference were published by Smith-Rose (1960). By October 1960 the membership had evolved to R. Emberson, V. Ilyin, J.A. Ratcliffe, H. Sterky, and R.L. Smith-Rose (secretary-general) for URSI; J-F. Denisse (chairman), V.V. Vitkevitch, J.H. Oort, and A. Unsold for IAU; and J.P. Hagen, L.G.H. Huxley, A.P. Mitra, and H.C. van de Hulst for COSPAR.

Under chairmen J-F. Denisse (1960–64) and Graham Smith (1964–1975) 13 meetings of a large IUCAF group were held all over Europe, plus a meeting in Washington D.C. in 1967.

Many articles pointed out the dangerous pollution of space around the Earth by the Needles proposal, and the likely effects on radio astronomy, optical astronomy, and space research (see Findlay 1962 and Lovell & Ryle 1962). Four papers appeared in *Astronomical Journal* in April 1961. A.E. Lilley (1961) analyzed the radio properties of an orbiting scattering medium. After considering Project WEST FORD and anticipating new communications and navigation systems employing powerful transmitters in earth satellites, Lilley's article concluded:

> The pursuit of basic science and the progress of space radio technology represent needs of man which must be advanced. For the impending interference a simple solution exists: allocation of clear frequency bands for basic science. This action is imperative and must ultimately rest on national and international agreements.

Figure 1 The six chairmen of IUCAF. *Top*: J-F. Denisse (1960–1964), F.G. Smith (1964–1975). *Middle*: J.P. Hagen (1975–1981), J.W. Findlay (1981–1987). *Bottom*: B.J. Robinson (1987–1995), W.A. Baan (1995–1999). In March 1999 Klaus Ruf became chairman.

IAU Involvement Denisse & Seeger (1961) gave an account of the formation of IUCAF to the 1961 IAU General Assembly in Berkeley. IAU Commission 40 formed a working group (Lilley, Seeger, Smith, Haddock, McClain, Molanchov, Gold, and Blum) to study the conditions under which the experimental belt of dipoles could be observed by radio astronomy observatories.

At the 1961 General Assembly the majority of members of IAU Commission 40 were completely opposed to Project WEST FORD. The members of Commission 40 were not convinced that the belt of dipoles would have a limited lifetime. This point of view was expressed in IAU resolutions proposed by Bondi, Christiansen & Gold (1961), and by Seeger & Pawsey (1961).

Resolution 1 said:

> Commission 40 views with concern the increasing contamination of the space around the Earth by radiating and scattering objects. It feels that no group has the right to change the Earth's environment in any significant way without full international study and agreement.

Resolution 2 said:

> Such projects should not be undertaken unless sufficient safeguards have been obtained against harmful interference with astronomy. Nevertheless, Commission 40 views with the utmost concern the possibility that the belt of dipoles proposed in Project WEST FORD might be permanent, and is completely opposed to such an experiment until this question is clearly settled in published papers and time has been given for their study. Whatever the limitations of present radio astronomical equipment, the Commission is inflexibly opposed to any steps that might permanently compromise future development in radio and optical astronomy.

The IAU executive committee announced a resolution (Denisse 1961):

> *Maintaining* that no group has the right to change the Earth's environment in any significant way without full international study and agreement;
> the International Astronomical Union *gives* clear warning of the grave moral and material consequences which could stem from a disregard of the future of astronomical progress, and *appeals* to all Governments concerned with launching space experiments which could possibly affect astronomical research to consult with the International Astronomical Union before undertaking such experiments and to refrain from launching until it is established beyond doubt that no damage will be done to astronomical research.

See also the reports of Smith-Rose (1962), Lovell & Ryle (1962), and Blackwell & Wilson (1962). The threat posed by WEST FORD was publicized in *New Scientist*, February 2, 1962, and updated in March 1, 1962.

Project West Ford Launches An abortive WEST FORD launch on October 21, 1961 (Morrow 1962) deployed on an Air Force Atlas-Agena B rocket carried

75 pounds of fine copper dipole fibers embedded in naphthalene. The package was expected to release the fibers slowly to form a belt at an altitude of 2000 miles. There was no sign that the dipole fibers dispersed from the package. The fibers remained clustered in five or six small clumps that were tracked by the MIT Millstone Hill UHF radar for several months.

A second WEST FORD launch scheduled for 1962 was delayed until May 12, 1963 (Morrow 1963). The 1963 launch put into polar orbit 400 million dipoles, more than half of which failed to separate into individual reflectors, remaining loosely tangled in small clusters or chains (Smith-Rose 1964c). The WEST FORD Project expired after these attempts.

The threats posed by Project WEST FORD to optical and radio astronomy and to space research brought home forcefully to scientists that strong international action was required to prevent major changes to the Earth's environment, particularly if these might be long lasting changes. It was a propitious time for the birth of IUCAF as an ICSU Inter-Union Committee to coordinate scientific needs for frequency allocations for scientific research. The threat of Project WEST FORD came from a military project. Later in this review we will discuss other military projects, or civil projects such as the Geostationary Meteorological Satellite, or commercial projects such as IRIDIUM.

The Committee on Radio Frequencies In the spring of 1961 the U.S. National Academy of Sciences and the National Research Council established the Committee on Radio Frequencies (CORF) "to serve as the United States counterpart to IUCAF" (Dellinger 1961). CORF first met on May 3, 1961 and was to play a major part in preparations for future WARCs.

3. SPACE WARC OF 1963

After the formation of IUCAF in 1960, the next ITU World Conference was the Space WARC of 1963. At the IUCAF meeting at the Royal Society London in October 1961 Smith-Rose (1961) reported that IUCAF "is now formally recognized as an active participant in the work of CCIR and the ITU." The meeting confirmed a recommendation, already provisionally forwarded to ITU, seeking the inclusion of radio astronomy and space science in the agenda of the 1963 Extraordinary Administrative Radio Conference to be held in Geneva from October 7 through November 8, 1963.

In 1959 Charles H. Townes and his group at Columbia University succeeded in establishing the laboratory frequencies of two radio spectral lines for the hydroxyl molecule. In the fall of 1963 Sander Weinreb applied his new correlation receiver technique on the MIT Millstone Hill 84-foot radio telescope. Weinreb, Barrett, Meeks, and Henry (1963) found absorption on October 15 at 1667.46 MHz in the direction of Cassiopeia A. The observers then found absorption at 1665.34 MHz, at 5/9ths of the strength at 1667 MHz. Interstellar OH molecules to be sure (Robinson 1965).

During the 1963 ITU conference the U.S. delegation was able to announce the discovery of the main OH lines at 1665 and 1667 MHz. A secondary allocation was made to radio astronomy in the 1664.4–1668.4 MHz band (shared with meteorological aids and meteorological satellites). Footnote F 353A described the discovery of the main OH lines and mentioned the intent to remove meteorological aids (meteorological balloons) from the 1664.4–1668.4 MHz band. The IUCAF Report on WARC-1963 appeared in *Nature* (Smith-Rose 1964a, 1964b).

In April 1964 Australian radio astronomers observing Sgr A discovered two "satellite" lines of hydroxyl at 1612.201 and 1720.559 MHz (Gardner et al 1964). At the time these satellite lines of OH were believed to be of lesser astrophysical importance than the main lines reported at WARC-1963. The satellite OH lines were later given a footnote allocation by WARC-1971.

4. MOLECULES IN SPACE: Millimeter-Wave Radio Astronomy

Great excitement greeted the discovery of the OH lines in 1963 and 1964. Theoreticians such as Bates & Massey (1947) had worked out the theory of two-body recombination, and we were comfortable to find OH lines at radio wavelengths to parallel CH and CN in optical spectra. Bates showed that the rate of three-body recombination in the interstellar medium was negligible.

Townes and his collaborators ignored Bates and found ammonia NH_3 at 23.7 GHz (Cheung et al 1968), and H_2O at 22.235 GHz (Cheung et al 1969). Formaldehyde H_2CO was found at 4.829 GHz (Palmer & Zuckerman 1969). Then came the 1970 discovery of CO at 115.271 GHz with the Kitt Peak 11-meter precision radio telescope (Wilson et al 1970). Over the next six years there was an avalanche of discoveries of molecular spectral lines (see the reviews by Rank et al 1971, Zuckerman & Palmer 1974, and Robinson 1976).

The flood of molecular line discoveries was timely in the preparations for the second "Space WARC" in 1971, discussed in the next section. The richness of the millimeter-wave spectrum in molecular lines also gave radio astronomers entrée to the top end of the radio spectrum, which other services had not begun to use. By 1972 there were 137 observed molecular lines (between 0.8 GHz and 173 GHz); most were assigned to 35 terrestrially identified molecules; eight of the lines were unidentified or produced by molecules that are transient or rare under laboratory conditions.

5. WARC-SPACE TELECOMMUNICATIONS 1971

Smith-Rose wrote to the ITU on March 4, 1969, requesting participation by IUCAF in the 1971 WARC on Space Telecommunications. The requirements of radio astronomy and space research were reviewed by Smith (1970) and in IUCAF Document 142 (Smith-Rose 1969). Improvements sought in the existing allocations were *(a)* at least part of each frequency band be made an exclusive radio astronomy allocation which is the same throughout the world; *(b)* improve and complete the series of bands throughout the spectrum; *(c)* provide wider bandwidths for observations in the bands at 2690–2700 MHz and above, and thus achieve higher sensitivities.

WARC-ST 1971 was held in Geneva June 7 to July 17 1971 and allocated frequencies up to 275 GHz. A detailed report (Horner 1971) listed the decisions affecting radio astronomy at WARC-ST 1971. The report's appendices give complete details of the allocations made to radio astronomy over the range of frequencies from 21.85 MHz to 240 GHz. (For a corresponding list of the frequencies allocated to space research see Horner 1972.)

A downward extension of the hydrogen band to 1400 MHz on a shared basis was made to cater for redshifts in emissions from more remote sources. Protection of the main OH lines was improved considerably by deleting meteorological satellite allocations in the band 1660–1670 MHz.

The 1971 ITU allocations covered these spectral lines above 1.4 GHz:

(a) By table allocation: Hydroxyl (1665 & 1667 MHz), Ammonia (23.7 GHz), Hydrogen Cyanide (86.3 & 88.6 GHz).

(b) By footnote allocation: Hydroxyl (1611.5–1612.5 and 1720–1721 MHz), Formaldehyde (4.829 GHz), Excited Hydrogen (5.763 GHz), Formaldehyde (14.489 MHz), Water Vapor (22.235 GHz), Excited Hydrogen (36.466 GHz), and Carbon Monoxide (115.271 GHz).

Recommendation Spa2-8 from WARC-ST 1971 was entitled "Relating to the Protection of Radio Astronomy Observations on the Shielded Area of the Moon." Arthur C. Clarke (1961) had suggested that lunar area as a location for radio astronomy. From 1974 CCIR studied the need to keep the radio spectrum quiet on the far side of the moon (CCIR Report 539-1 and CCIR Recommendation 479-1). When commercial pressures pollute the whole terrestrial radio spectrum and the sky contains swarms of radiating satellites, the far side of the moon would become the last oasis for radio astronomy.

6. INTERFERENCE FROM SATELLITES AND AIRCRAFT

6.1 Broadcasting Satellites

The allocation of the 2670–2690 MHz band to radio astronomy at WARC 1971 (on a shared basis) was nullified by new allocations for the Broadcasting Satellite Service in the 2500–2690 MHz band. Out-of-band energy from broadcasting satellites up to 2690 MHz would also cause interference to radio astronomy in the 2690–2700 MHz band, which was allocated exclusively to radio astronomy. The Broadcasting Satellite Service was unable to guarantee that such interference would be kept below limits recommended by the CCIR; nor would they agree to a guard band of several megahertz. During the Project WEST FORD planning, a television picture had been sent in April 1962 from California to Massachusetts using the ECHO-1 space balloon (Morrow 1963). This had shown the feasibility of radiating TV from a satellite in geostationary orbit to a whole hemisphere of the Earth.

The chairman of IUCAF (Smith 1972a) wrote to all radio astronomy observatories about the very serious threat to observations using one of the most important frequency bands allocated to radio astronomy. The WARC 1971 allocation to broadcasting satellites was taken despite strong objections by IUCAF and others representing the interests of radio astronomers.

Smith (1972b) discussed how the launch of the sixth Applications Technology Satellite (ATS-F) could threaten radio observations of the universe. The ATS-F, broadcasting at 2670 MHz, was a precursor to satellites that would broadcast television programs direct to domestic receivers. Smith voiced the concern of radio astronomers over the ATS-F affair because of the cavalier treatment of the international regulations governing allocation of radio spectrum frequencies. The broadcasting signal would spill into the exclusive radio astronomy band at a level 30 times the permissible level in the CCIR report to the ITU for the 1971 WARC. Smith quoted a radio astronomer who was deeply involved in the protection of the RA bands as saying the ATS-F was "a sad and ironic example of the rapidly growing misuses of the radio spectrum." NASA agreed to insert a filter in ATS-F to protect the radio astronomy band (Howard 1973). The satellite was launched as ATS-6 in May 1974.

6.2 Satellite Beacons

Not all radio astronomers were aware of the great danger of emissions from spacecraft in or near ITU allocated radio astronomy bands. They had not taken in Graham Smith's dire warnings on 22nd January 1972. On 22nd March 1972, Paul Wild wrote to Bernie Mills: "During the past year I have been in touch with American authorities investigating the possibility of their providing a radio astronomy calibration service consisting of one or more radio beacons located in a geostationary satellite. . . . Our specific interest is for an aid to calibrate the phase and amplitude of the Culgoora radioheliograph, and we need three frequencies, 160, 80, and 43.5 MHz. I am now writing to other radio astronomers in Australia to find out whether there are requirements for other frequencies and, if so, how important the requirement is judged to be."

On March 23 Bernie Mills replied:

> I was very disturbed to receive your letter about the proposed beacons located in a geostationary satellite. This could be a very dangerous precedent which, although it might provide certain groups immediately with easier calibration procedures, could also lead eventually to a host of special purpose beacons polluting the whole frequency spectrum. Radio astronomers should be opposing this concept, not supporting it.

Mills contacted IUCAF. Graham Smith wrote to Paul Wild:

> I hear from Bernie Mills that you are exploring the idea of using calibrating radio transmitters in satellites. My initial reaction is much the same as his.

> . . .I think perhaps the correct approach would be to make a case for such transmitters and ask for a discussion in IUCAF or in Commission V of the URSI General Assembly.
>
> We are planning to have a meeting of IUCAF during the Warsaw (URSI) assembly, and I would be happy for this and any other matters to be discussed if you wish. At the moment the main topic seems to be the problem of broadcasting satellites. . . . I would be embarrassed about trying to stop one transmitter and encourage another during the same meeting of IUCAF.

Martin Ryle joined in on March 29:

> I must say that I am appalled at the idea. I do not see how you could operate such a system.
>
> . . .I agree with Bernie that radio astronomers have a good record as conservationists, and that to intentionally produce radiation in radio astronomy bands and from a satellite is about as serious a pollution as one could devise!
>
> . . .I do not see the point of it; Nature has provided us with a large number of sources—many of which are of very small angular size. Special observations (both optical and radio) can now locate these to better than 1″ arc. . . .they are there all night, every night—and you don't have to seek permission from the world's radio astronomers before you have a brief period of calibration. . . .
>
> The I.T.U. has recognized radio astronomy and has provided me with the right to observe on internationally agreed bands. I intend to fight to preserve that right!

On March 20, 1972 Frank Kerr wrote to Bill Howard at NRAO, who had circulated a letter to CORF members. John Hagen was chairman of CORF, due to meet on May 5, 1972:

> The Paul Wild–John Hagen proposal to instrument a NASA satellite with calibration beacons operating in radio astronomy bands is an attractive one. . . . The possibilities are certainly worth exploring. At the same time, we must be quite sure that the system contains a completely foolproof off-switch for each frequency!

The exchanges of letters continued. Mills wrote to Graham Smith on April 18, 1972:

> Needless to say, I am thoroughly opposed to the concept of radio beacons in radio astronomy bands and, among Australian radioastronomers, I know that my feelings are shared by Christiansen, Bolton and Robinson so that there seems little prospect of Paul Wild's proposal making much headway at this end. The danger would seem to be with the U.S. radioastronomers.

Ultimately, world opposition to the beacon proposal led to the wires to the beacons being cut while the NASA satellite was on the launch pad.

6.3 Aircraft Landing System at 5 GHz

The second Space WARC in 1971 not only allowed broadcasting satellites adjacent to the 2700 MHz radio astronomy band. That WARC had also made an allocation for aeronautical radionavigation from 5.0 to 5.25 GHz. Immediately below 5 GHz was another very important radio astronomy band. WARC-1971 had allocated 4.7 to 4.99 GHz as a band for radio astronomy, shared with fixed and mobile services; 4.99 to 5.00 GHz was a primary radio astronomy allocation.

The International Civil Aviation Organization (in Montreal) announced in 1972 an international competition to design a 5 GHz microwave landing system (MLS), for use at airports, to replace the old Instrument Landing System operating at 200 MHz. Radio astronomers were concerned that out-of-band emissions from MLS would cause harmful interference to their observations below 5 GHz.

Paul Wild had just become Chief of the CSIRO Radiophysics Laboratory in Sydney. The winds of economic rationalism were blowing. So Paul entered CSIRO in the ICAO competition, and was ultimately successful. High-caliber engineers such as Brian Cooper and John Brooks were taken from the radio astronomy program at CSIRO to design and test the MLS system.

Fortunately, by 1998 only a handful of MLS systems have been installed at airports. One reason is that air traffic has not grown as ICAO projected, and airports are not required to handle very high arrival and departure rates. Also, as each year passed, the possibility of using the very accurate GPS and GLONASS satellite navigation systems became a better alternative to MLS. The accuracy of differential GPS is excellent.

6.4 The GMS Meteorological Satellite

A bright spot in the 1970s was successful negotiations with Japan on the out-of-band transmissions from the Geostationary Meteorological Satellite. Effective filtering of wide unwanted sidebands was shown to be feasible. Each day television viewers in Asia and the South Pacific see a satellite image of the Earth. They can see a typhoon approaching Guam, or a cyclone bearing down on Fiji. Great armchair viewing.

The GMS Meteorological Satellite was to be constructed and launched by Hughes Aircraft Company and operated by Japan. Its central frequency was to be 1681.5 MHz. That is of no concern to Radio Astronomers. But the modulation on the image beamed down to Asia and the South Pacific would have extended sidelobes that would cause harmful interference to radio astronomy observations in the OH band 1660 to 1670 MHz.

At the time the GMS satellite was being designed, IUCAF correspondent Brian Robinson contacted the Japanese Meteorological Agency and encouraged them to build a filter to protect the OH band. Yasushi Horikawa (National Space Development Agency of Japan) and Seiji Yoshimoto (Nippon Electric Company) discussed the problem. When Hughes Aircraft Company engineers said that such a filter could not be built, the Japanese decided to design and build it. Vacuum chamber tests at the end of 1975 showed that the radio astronomy specifications could be met.

When the satellite was launched in 1977, Horikawa and Yoshimoto came to the Parkes 64-meter radio telescope. Observations made then of the GMS satellite are reproduced in Robinson & Whiteoak (1979). In the radio astronomy band the filter gave 60 decibels attenuation of the GMS emissions. The radio astronomers were delighted. The Japanese engineers were delighted. A win-win situation.

6.5 SSU Series Satellites—Interference at 1420 MHz

In April 1976 the U.S. launched three "SSU" satellites, which produced strong interference to Canadian radio astronomy observations at 1420 MHz (Argyle et al 1977). The signals were a billion times greater than the hydrogen emissions being studied. The Canadians protested to the U.S. that the satellites were transmitting, in contravention of ITU allocations, close to the band reserved solely for radio astronomical observations of neutral hydrogen.

Investigations showed that the satellites stored large amounts of data during their 107.5 minute orbit, and dumped the data (when controlled from the ground) near Alaska, the Pacific Northwest and Midwestern United States. Argyle et al said that the signals are "in contravention of the International Telecommunications Union's Table of Frequency Allocations. . . .Therefore, we urge scientists in the United States who are concerned with the orderly management of the electromagnetic spectrum to press their government to limit the use of bands near radio astronomy allocations to ground-based services." This was a salutary warning to radio astronomers as the preparations for the next WARC (in 1979) got under way.

7. DOWNSIZING OF IUCAF IN 1973

Smith-Rose (1972) reported to the 1972 URSI General Assembly in Warsaw that "IAU, URSI, and COSPAR have agreed to reduce the number of their representatives on IUCAF to two and it is intended to have an annual meeting beginning in 1973."

This decision, for financial reasons, removed many influential radio astronomers from IUCAF and cut down on the number of meetings. At the 1972 General Assembly in Warsaw, URSI appointed J.W. Findlay and J.P. Hagen as its IUCAF representatives. In 1973 IAU appointed Graham Smith and Richard Wielebinski as its representatives. COSPAR representatives were Fred Horner and M.M. Thue.

With the Cold War mentality of the time, there was no Soviet representation on IUCAF after 1972. The exclusion of Eastern Europe was odd, given that the Communist Bloc had a significant vote at ITU conferences on frequency allocations. Graham Smith became Astronomer Royal in 1975, and his IAU slot on IUCAF was filled by Gart Westerhout. John Hagen became chairman of IUCAF at the Paris meeting in October 1975.

7.1 IUCAF Correspondents

At the IUCAF meeting in Konstanz (26 May 1973) an important decision was made to appoint IUCAF Correspondents in 27 countries (Minnis 1973). This was a recognition that, when frequency allocations were considered by the ITU at WARCs, only national administrations have a vote. Bodies like IUCAF are recognized at WARCs; they can speak and lobby, but not vote. The IUCAF Correspondents would be kept informed of IUCAF policy, and communicate the needs of radio astronomy and Space Science to their national spectrum administrators. The 1973 reorganization reduced the effectiveness of IUCAF, but gave it a coordinating role to the network of Correspondents. A list of the Correspondents was published by Minnis (1974).

7.2 WARC 1979: A WARC General

The ITU proposed a general WARC for 1979, to consider all frequencies up to 285 GHz. It would be like WARC 1959—considering all frequencies, all services. No holds barred.

IUCAF began discussing WARC-1979 at the Bonn meeting July 29, 1974. IUCAF proposed discussing with its correspondents "questions concerned with, for example, the usefulness of existing frequency allocations, the need for changes in the bandwidths available at present, and requirements for allocations to meet new scientific needs. The increasing use of artificial earth satellites which emit radio frequency energy for various purposes represents a growing interference problem, especially when wide-band emissions spread into adjacent bands and cause interference. IUCAF is actively engaged in studying current problems of this kind and the potential sources of interference in satellites to be launched in the future."

A meeting of IUCAF to discuss preparations for WARC 1979 was held in 1976 at the IAU General Assembly in Grenoble. John Findlay conducted the meeting (Findlay 1976, Horner 1976).

7.3 IAU Priorities for Molecular Lines

The members of IUCAF (Hagen, Findlay, Westerhout, Wielebinski, Horner and Thue) were not conversant with the flood of discoveries of molecular spectral lines. By 1976, 220 molecular lines were known in the radio spectrum.

IAU Commission 40 set up a Working Group, chaired by Brian Robinson, to determine the priorities to be given to the molecular lines during IUCAF's preparations for WARC 1979. By 1979 around 600 molecular lines were known between 0.8 and 346 GHz. An IAU list of 30 key spectral line frequencies was agreed to at the 1979 IAU General Assembly in Montreal (Robinson & Whiteoak 1979, Westerhout 1979). The IAU submitted the list of key spectral lines to CCIR in Geneva. The listing was agreed to by the relevant study group and incorporated in CCIR Recommendation No. 314. As previously noted, CCIR Recommendations carry great weight in the deliberations at a WARC.

The IAU Working Group continued to evaluate the key spectral lines at every IAU General Assembly for the next 21 years. Each time the revisions were adopted as Recommendations by CCIR (or, as it is now known, ITU-R).

7.4 The CORF "Green Book"

The U.S. National Academy of Sciences Committee on Radio Frequencies (CORF) produced the "Green Book," the key document for the radio astronomy case at WARC 1979 (and the CCIR Special Preparatory Meeting of 1978).

The chairman of CORF was Bernard F. Burke. Members were Alan H. Barrett, Otis Brown, William C. Erickson, John P. Hagen (chairman of IUCAF), David C. Hogg, Hein Hvatum, Frank J. Kerr, Nancy G. Roman, and, serving as secretary, Richard Y. Dow. The hard work was done by the Sub-Committee on radio astronomy: William C. Erickson (chairman), Donald C. Backer, Alan H. Barrett, Barry G. Clark, Thomas A. Clark, Michael M. Davis, Andrea K. Dupree, Alan T. Moffat, and A. Richard Thompson. The Green Book was distributed to all IUCAF members and correspondents. In most cases they interacted with their national telecommunication administration to have the radio astronomy position inserted into their country's submission to WARC 1979. Those "input document" submissions to the ITU in Geneva were numerous and weighty (in kilograms). Reviewing the whole spectrum was a monumental task.

7.5 WARC-1979 in Geneva

A summary of what the radio astronomers sought from WARC 1979 was published by Robinson & Whiteoak (1979). WARC 1979 ran from September 24 to December 6, finishing a week late. IUCAF delegates who were unattached to any national delegation and could express individual views on behalf of the scientific community were John Hagen, Marcus Price, and John Findlay. Some members of IUCAF, IUCAF correspondents, or other scientists were members of national delegations: Bajaja (Argentina), Block (ESA), Doherty (Canada), Dubinski (USSR), Grahl (West Germany), Horner (U.K.), Kahlmann (Netherlands), Okoye (Nigeria), Pankonin (USA), Pezzani (France), Schilizzi (Netherlands), Swarup (India), Thue (France) and Whiteoak (Australia).

Two meetings of radio astronomers were called by IUCAF in the early stages of the WARC, but most work was carried out by personal contacts. For some it was instantaneous training in diplomacy. A report on WARC-1979 was published by Fred Horner (1980). An extensive report was also published by Bodson et al (1981). Horner's report says of radio astronomy and space research:

> The overall outcome is widely considered to be satisfactory for these sciences; indeed the general opinion is that they have received very favorable treatment, but some provisos will be mentioned below.
>
> There was a strong and cohesive radio astronomy group . . . five (radioastronomers) were involved for various periods as representatives of IUCAF.

> . . . In the case of radioastronomy there was a significant increase in the number of (frequency) table allocations. . . . In space research . . . there are considerable gains in allocations for sensing of the Earth's surface and atmosphere by both radiometric and radar techniques.

WARC 1979 allocated radio astronomy 16 bands between 322 to 328.6 MHz and 105 to 116 GHz. Allocations "by footnote" were made to 18 bands between 140 GHz and 348 GHz. The WARC also approved a Dutch proposal for Article 36 in the Radio Regulations, setting out the basic operation and needs of radio astronomy. There were also sections on "radio astronomy in the Shielded Zone of the Moon" and "The Search for Extraterrestrial Emissions" plus new definitions of interference and "unwanted emissions."

At WARC 1979 India had proposed that the band 322–328.6 MHz be allocated to radio astronomy. The band contains the important spin-flip transition of Deuterium. The cosmological importance of Deuterium was, and remains, high. The NATO countries and the USA supported this 327 MHz allocation: they knew that the Soviet Union had an extensive radar network around the Middle East at 327 MHz. On May 1, 1960, it had tracked Gary Powers' U2 spy plane from Pakistan to Sverdlovsk, 1200 miles inside Soviet territory. A re-allocation of the 322–328.6 MHz band to radio astronomy was voted through at WARC 1979.

7.6 Recommendation 66 of WARC-1979

Within ITU activities, "Recommendations" are the highest level of directive. Also the World Administrative Conferences are the highest level of authority. The ITU Secretariat and organs of the ITU like CCIR must take note of recommendations—especially if they come from a WARC.

When WARCs allocate frequency bands to different users ("services") it is hard to avoid incompatible neighbors. We have already seen the problems of allocating to satellite broadcasting a band that is next to an important radio astronomy band (2700 MHz); or an aircraft landing system next to another important radio astronomy band (5000 MHz); or the GMS meteorological satellite close to the OH band (1660–1670 MHz). Similar problems arose during WARC-1979.

The hypersensitivity of radio telescopes to low-level "unwanted," spurious and out-of-band emissions leaves them particularly exposed to these emissions. Throughout the "Radio Regulations"—the allocations made by WARCs—there are "footnotes." Every footnote relating to radio astronomy says: "Emissions from space or airborne stations can be particularly serious sources of interference to the radio astronomy Service." So WARC-1979 issued "Recommendation 66" as a directive to CCIR to carry out studies of the Maximum Permitted Levels of Spurious Emissions. Rec. 66 directed the CCIR to carry out these studies of space services transmissions "as a matter of urgency."

CCIR did absolutely nothing. The vested interests of the satellite service operators made sure that nothing happened! We will see that, thirteen years later, WARC-1992 repeated the instruction to CCIR in the form of Recommendation 66-2. We'll see how committees set up by CCIR (now renamed as ITU-R) sabotaged the process, and that Recommendation 66 from the ITU has been issued yet again by WRC-1997.

8. ORBITAL AND MOBILE WARCS: 1983–1988

From 1976, IUCAF meetings were held every three years, at the URSI General Assemblies in Helsinki (1978), Washington (1981), Florence (1984) and Tel Aviv (1987). After the great effort made at WARC-1979 and the very satisfactory outcome, radio astronomers looked forward to a 20-year period of creative discovery to the outer fringes of the universe. The next WARC-General was expected to be in 1999—far away! New radio telescopes had been built: the Very Large Array was commissioned in January 1980, and the opportunities for new observations were tantalizing. The Australia Telescope was funded in 1982.

But a series of crucial WARCs was being held, dealing with allocations to mobile and satellite services. These were WARC-1983 (MOBILE 1), WARC-1985 (ORBITAL 1), WARC-1987 (MOBILE 2) and WARC-1988 (ORBITAL 2). Unfortunately there was little IUCAF involvement at these WARCs.

Plans for the Broadcasting Satellite Service in the 12 GHz band (and its feeder links) were produced by the WARCs in 1983 and 1988. WARC-1988 looked at a broadcasting satellite allocation (HDTV) at 23 GHz—adjacent to the important 22 GHz transition of water vapor where H_2O masers were being found all over our Galaxy and in distant galaxies. At WARC-1987 allocation was made to a radiodetermination satellite in the 1612 MHz OH band. But a key footnote was added saying that "Harmful interference shall not be caused to stations of the radio astronomy Service using the band 1610.6–1613.8 MHz by stations of the radiodetermination-satellite service."

8.1 IUCAF Stand on the VEGA Mission in 1984

In 1984 IUCAF took a strong stand against the Soviet VEGA Mission (Findlay 1984a). In the build-up to Comet Halley's appearance in 1986, a Soviet VENERA spacecraft was to drop off probes at Venus in June 1995 and continue on a trajectory to intercept Comet Halley. The problem was that the VEGA project managers planned to transit radio signals at 1667.8 MHz, falling within the 1660–1670 MHz band where radio astronomy has a primary, world-wide allocation. The managers had chosen 1667.8 MHz because they knew that radio telescopes in many countries were equipped with extremely sensitive receivers in this band. They saw these radio telescopes as a readily available network of tracking stations for their mission.

CORF, chaired by David Staelin, expressed great concern about the frequency chosen by Vega. IUCAF discussed the Soviet plan during the 1984 General Assembly of URSI in Florence. Radio astronomers could not sanction the use of transmitters within a passive band. It was just like the satellite-beacon proposals of 1972, and undermined the strong IUCAF objections to broadcasting satellites adjacent to the 2700 MHz radio astronomy band. The URSI Council met in Florence and resolved "to urge the Member Committees of COSPAR, IAU and URSI to work with IUCAF as a consultative body when planning any active radio frequency usage in future scientific missions which may cause interference to passive observations" (Findlay 1984a).

Also URSI "resolves, in view of the specific danger of interference to radio astronomy from space-based radio transmissions, to urge all those concerned in the design of experiments requiring radio transmissions from space to consult with IUCAF at the planning stage to ensure that the protection of sensitive passive radio observations which has been acquired through wide cooperation and with great effort is not jeopardized in the future."

The linking of the Vega mission to the comet encounter in March 1986 made the mission time-critical and the IUCAF meeting in August/September 1984 was too late to alter this frequency. The Vega mission was launched in December 1984. Most radio astronomy observatories boycotted the mission, depriving the Soviet managers of the convenient world-wide tracking network they had hoped to exploit. Radio observatories wished to search for hydroxyl molecules in Comet Halley and its tail, and were concerned that the in-band transmissions from the Vega satellite would compromise the observations.

A proposal emanating from Jodrell Bank (initiated by Ray Norris and John Ponsonby) was to transmit a strong beam of radiation at Comet Halley at 1.6 GHz to investigate the pumping of the OH masers. A French student at Jodrell Bank, Laurent Pagani, did an excellent thesis study and came up with a detailed proposal for sweeping a radio beam in frequency across the line profile of the cometary maser and studying the time it took the comet to recover. It was an elegant proposal to do a laboratory-type measurement on a cosmic maser source for the first time. Eric Gerard had the job of taking this idea to the International Halley Watch Committee (meeting in the U.S.) where it was opposed unanimously—everyone was afraid the comet might not recover at all.

While passing Venus, the Vega mission had 1667.8 MHz transmitters on two balloons and another on the spacecraft. The balloons drifted in the upper atmosphere winds of Venus and, from differential VLBI between the spacecraft (a known orbit) and the balloons, quite a lot was learned about the atmosphere and winds. The Vega VLBI project had Bob Preston from JPL as its principal investigator, and the Jodrell Bank telescope took part.

8.2 Spread-Spectrum Modulation

From 1983 to 1988, at the MOBILE and ORBITAL WARCs, communication engineers had seized the opportunities they saw in using transmitters on satellites to illuminate the earth. They had also embraced "spread-spectrum modulation." Originally developed by the military in the 1950s, spread-spectrum modulation appeared to be a panacea for everything (Pickholtz et al 1982). The high-speed modulation produced extended unwanted/spurious/out-of-band emissions that interfered seriously with those listening in nearby or adjacent bands. The energy from the spread-spectrum sidebands fell off slowly with the frequency separation x from the carrier frequency—only as the square of $(\sin x/x)$.

8.3 WARC-1988 ORB 2

Attempts were made by IUCAF to make up lost ground at ITU WARC ORB 88. The sole IUCAF representative at the 1988 WARC was B.H. Grahl. Ten years on, IUCAF is still sorting out how to share bands allocated to satellite and mobile users by the WARCs of 1987 and 1988.

8.4 GPS: The Global Positioning Satellites

The U.S. Air Force designed and launched a family of navigation satellites designed to give an accurate position of a receiver on or near the earth. The motto over the entrance to GPS Headquarters said: “Two bombs in the one hole.” The U.S. Air Force demonstrated that feat in a raid on Baghdad in January 1991.

The GPS emissions had extended sidebands, which caused harmful interference in the OH bands 1610.5–1613.8 MHz and 1660–1670 MHz. Protests from radio astronomers were heeded. The space shuttle Challenger disaster of January 28, 1986 took three GPS satellites into the Atlantic Ocean. After the Challenger disaster no GPS satellites were sent into orbit until 1989.

IUCAF made a formal protest to IFRB in Geneva in February 1990. Canada also made a formal protest to the U.S. Government in March 1990 about harmful interference, and the International Frequency Registration Board in Geneva was informed. Sweden also complained. The U.S. Department of Commerce confirmed that the interference originated on older “Block I” GPS satellites and that the system was being upgraded. Canada also complained to the USSR about interference from GLONASS satellites (see the next section).

By 1993 the sideband emissions of a new series of “Block II” GPS satellites were all filtered to remove the harmful interference with OH observations. The spurious signal levels were 38 decibels lower than those of their predecessors. Spectra of GPS emissions before and after filtering are shown by Ponsonby (1991).

One benefit of GPS emissions was that they made effective use of spread spectrum technology. All carriers had the same frequency (1574.4 MHz). The spread-spectrum modulation for each satellite was different, but there was no mutual interference.

8.5 Global Navigation Satellite System—GLONASS

A navigation system with satellites launched by the USSR Space Forces from 1983, GLONASS was similar to the U.S. Air Force GPS. The important differences were *(a)* each satellite emitted on a different frequency, with the carrier frequencies spread over the range of 1597–1617 MHz; *(b)* the level of the interference was incredibly high because the range of carrier frequencies stepped right through the radio astronomy allocation of 1610.6 to 1613.8 MHz; *(c)* the satellites were "frequency mobile"—no filtering seemed possible, whereas filtering had been possible with the GPS satellite emissions.

9. IUCAF ACTIVITY FROM 1980 TO 1987

The list of radio spectral lines of the greatest astrophysical significance was extended at the 1982 IAU General Assembly in Patras (Robinson 1982) and conveyed to CCIR. Fifteen lines were added between 279 and 691 GHz on the expectation that a future WARC would consider this very high frequency range.

Fred Horner, a COSPAR representative on IUCAF, had become chairman of CCIR Study Group 2 (dealing with radio astronomy) in 1980. At the 1987 IUCAF meeting in Tel Aviv, Fred commented that IUCAF had not provided any advice to CCIR in the previous three years. What had IUCAF been doing?

The minutes of the 1987 Tel Aviv meeting reveal despondence. Regarding the IUCAF correspondents system, the minutes record: "It only worked once, before the 1979 WARC. It's pretty useless otherwise." IUCAF funds were low, and John Findlay asked, "Should we quit?"

At the Tel Aviv meeting Hans Kahlmann announced European proposals to ITU for a major WARC in 1992. It became clear that IUCAF had a lot of work to do, that it needed to have more members and that more funds were required from URSI and IAU. John Findlay's term as chairman of IUCAF was to end in 1989, just when the bulk of the preparatory work for the major WARC would be needed. So discussions began in Tel Aviv about replacing John as chairman in 1988. A ballot of IUCAF members was held in March 1988, and Brian Robinson was elected chairman.

New members were appointed to IUCAF, and membership increased to ten: B.H. Grahl, H.C. Kahlmann, R.M. Price, and B.J. Robinson for URSI; B.A. Doubinsky, N. Kaifu, V.L. Pankonin, and G. Swarup for IAU; F. Horner and S. Hieber for COSPAR.

It was timely to have a Soviet member of IUCAF, after the long gap since the reorganization of IUCAF in 1972. The network of IUCAF correspondents was revived, with correspondents in 35 countries. Eastern Europe is well represented, but there is only one correspondent from Africa. URSI and IAU increased their annual funding of IUCAF, and additional funds were obtained from ICSU for the extensive preparations for WARC-1992.

9.1 The Foundation of CRAF

At the 1987 meeting of IUCAF, Hans Kahlmann announced the foundation of a European parallel to CORF and link to IUCAF. The moves to create a EuroCORF began in 1987 at a meeting in Paris. H.C. Kahlmann was the first chairman, and T.A.Th. Spoelstra was the secretary. The timing suggests that this move was a European preparation for WARC-1992. Another factor was the need for concerted European action against the strong interference from Soviet GLONASS satellites.

Those involved in the foundation of CRAF were Kahlmann, Schilizzi, and Spoelstra from the Netherlands; Paul Burgess, Cohen, and Ponsonby from the United Kingdom; Daigne, Kovalevsky, Pezzani, and Pick from France; Ellder from Sweden; Gorgolewski from Poland; Grahl and Ruf from Germany; and Tomassetti from Italy. The IUCAF (Findlay, Horner), CORF (Price), NSF (Gergeley) and ESO/SFCG (Block) contributed to the effort.

In March 1988 the European Science Foundation (ESF) accepted in principle a proposal that CRAF become an ESF Committee with the name "ESF Committee on Radio Astronomy Frequencies." This paralleled the link between CORF and the U.S. National Academy of Sciences. One represented Europe, the other the United States. Internationally, the position was coordinated by IUCAF.

Two members of CRAF (Kahlmann and Cohen) became full members of IUCAF to reinforce the collaboration. Other members of CRAF became correspondents of IUCAF. CRAF met frequently and has continued to meet two or three times a year, while CORF in the U.S. meets but once a year.

Through its national members, CRAF hoped to influence the WARC-1992 positions of individual countries (given that only countries affiliated with the ITU have the right to vote at WARCs). Hans Kahlmann retired as chairman of CRAF in 1995, and Jim Cohen was appointed chairman. Titus Spoelstra continued as secretary; in 1997 he became a full-time CRAF frequency manager for European radio astronomy.

10. ITU WORLD ADMINISTRATIVE RADIO CONFERENCE 1992

The 1989 Plenipotentiary Conference of ITU in Nice resolved to hold a special World Administrative Conference in Spain in 1992 (WARC-1992). Such a wide-ranging WARC had not been expected until 1999 (in keeping with the established pattern: 1959, 1979, 1999, and so on). But the increasing pace of technological change forced the ITU to hold the conference earlier, to embrace satellite mobile communications, digital radio broadcasting, high definition TV and other technologies not envisaged at WARC-1979. The conference agenda for WARC-1992 was drawn up in June 1990.

10.1 IUCAF Preparations for WARC-1992

The re-igniting of IUCAF to prepare for a wide-ranging WARC began at the 1988 IAU General Assembly in Baltimore. After the IAU assembly, IAU Colloquium 112 discussed "Light Pollution. Radio Interference and Space Debris" (Crawford 1991).

Strenuous activities were needed for the input to CCIR Study Group 2 in 1989. More work was done at an IUCAF meeting during the 1990 URSI General Assembly in Prague. That general assembly was followed by key meetings in the Washington area of CCIR Working Parties and a meeting of SFCG (Robinson

1990). A second CCIR Working Party meeting was held in Geneva in February 1991. These meetings kept the members of IUCAF very busy.

In March 1991 the CCIR held a major conference in Geneva to establish "The Technical and Operational Bases for the World Administrative Radio Conference 1992." Represented by Robinson and Kahlmann, IUCAF played a major part in this meeting, which would generate technical decisions that would circumscribe the political decisions to be faced at WARC-1992 (Robinson 1991).

continued to be a busy year for IUCAF. It participated in the SFCG meeting in October to coordinate the preparations for WARC-1992 on space research and space exploration. Then discussions about GLONASS were held with the Russian Space Forces in Moscow in October. IUCAF took part in CCIR meetings in Geneva during October 1991, converting existing CCIR reports into recommendations that would carry legal force at WARC-1992. Finally, in negotiations with Motorola Corporation, IUCAF and Motorola tried with little success to find a *modus vivendi* between vital astronomical observations of OH (related to star formation and to the late stages of stellar evolution) and a proposed mobile telephone system linked by a swarm of low-flying satellites—fundamental knowledge versus big bucks.

A summary of the status of radio astronomy prior to WARC-1992 was published by Thompson, Gergely, and Vanden Bout (1991).

10.2 WARC-1992

IUCAF was heavily involved in WARC-1992 itself, from February 3 to March 4, 1992 (Robinson 1992). Hans Kahlmann, Berndt Grahl, Brian Robinson, Govind Swarup, Dick Thompson, and Boris Doubinsky comprised the IUCAF delegation, supported by IUCAF correspondents Tom Gergely, Ramesh Sinha, and Rob Roger. At the WARC the status of space research and radio astronomy was significantly enhanced between 137 and 3000 MHz and above 13.5 GHz. Delegates from 125 countries clearly recognized the importance of scientific use of the radio spectrum in the face of increasing pressure from telecommunications, broadcasting, and navigation interests, particularly when the proposed commercial transmissions are from satellites.

IUCAF delegates became immersed in the projected characteristics of digital radio broadcasting, high definition TV, and the "big LEOs" and "little LEOs"—mobile communications facilitated by low-earth-orbit satellites. WARC-1992 made allocations for radio astronomy up to 285 GHz; these were mainly CO bands.

Despite the efforts of CRAF, there were moves in 1990 through 1991 to bind the 28 European countries to a single point of view. This solid block of votes was seen as a counter to the U.S.-Canada-Mexico cast-iron position, or the Russia-Belorussia-Ukraine cast-iron position. At WARC-1992 the position of the 28 European countries discounted the recommendations of CRAF and ran contrary to the needs of radio astronomy. However, the U.K. voted independently on some key radio astronomy issues. The rock-solid position of the European bloc (now 27 countries) held until 1 a.m. on the morning of the last day of the WARC.

Recommendation 66, the WARC-1979 directive to CCIR to examine spurious and unwanted emissions, was renewed by the 1992 WARC.

10.3 Illegality of GLONASS Transmissions

Prior to WARC-1992, radio astronomy use of the most important 1612 MHz satellite line of OH had been authorized by Footnote 352K in the Radio Regulations, first inserted by the "Space WARC" of 1971. The footnote warned that "Emissions from space and airborne stations can be particularly serious sources of interference to the radio astronomy service." But later WARC-1979 inserted Footnote 352A, reserving the whole band 1610–1626.5 MHz on a worldwide basis for "airborne electronic aids to air navigation and any directly associated ground-based or satellite-borne facilities."

In April 1983 the Soviet government used the regular ITU coordination procedures to advise of its plan to operate its Global Navigation Satellite System (GLONASS). Only one country responded to the announcement of this satellite system, and the response was submitted after the 45-day cut-off for objections. The U.S. objection, in August 1983, expressed its concern for the impact on radio astronomy, and requested more information on the GLONASS signal character. The USSR did not respond.

No radio astronomer outside the U.S. noticed the announcement of the USSR system. Then the horrific interference produced by GLONASS satellites near 1612 MHz closed down radio astronomy observations of the OH line. Two "footnote" ITU allocations had equal legal status, and radio astronomers could only lament their oversight. By January 1984 Vernon Pankonin identified that eight GLONASS satellites were operational. Epherimedes of the satellites were difficult to obtain and the interference was unpredictable (Crane 1985).

The first change to the GLONASS situation occurred in May 1991, when the Russian government approached the ITU seeking improved status for GLONASS in the 1597–1617 MHz band. This time IUCAF was immediately aware of the request to ITU, and in June 1991 ten countries organized to oppose the Russian request to ITU, which then lapsed. IUCAF argued that GLONASS should contain its emissions to the 1559–1610 MHz band, which had been allocated by WARC-1979 to radio navigation satellites and aeronautical radionavigation.

IUCAF members Brian Robinson and Boris Doubinsky confronted the Russian Space Forces at a meeting in Moscow in October 1991, under the umbrella of Academician V.A. Kotelnikov. After much negotiation, the Russians agreed "to consider all possibilities to decrease the interference to the radio astronomy in mentioned frequency band in the process of upgrading of the GLONASS system." They undertook to eliminate the out-of-band emissions of the GLONASS system "beginning from 1994 in process of replacement of the Space apparatuses with new ones equipped by improved filters."

At WARC-1992 the situation changed dramatically. While the conference was going through a very moribund state, locked in some stalemate between Europe and the rest of the world, an Australian proposal to enhance the status of radio astronomy at 1612 MHz was approved. During the crucial vote, the Russian, Belorussian, and Ukrainian delegates at the WARC were deep in discussing something else, had taken off their earphones and were not listening to the simultaneous translation of the presentations. With that vote, radio astronomy gained full primary status in the band. Services with secondary or (lower still) footnote status could not interfere with a primary service: GLONASS had only footnote status.

In June 1992 Brian Robinson, Boris Doubinsky, and Willem Baan confronted the Russian Space Forces again, at a second meeting in Moscow. All proposals from IUCAF were greeted with a stony "*niet*." So it was arranged that a delegation from the Space Forces and the Institute of Space Device Engineering would visit the Jodrell Bank telescope in November 1992 to witness the interference for themselves. During the tests at Jodrell Bank the Space Forces switched off or retuned nine of the 13 GLONASS satellites and observed the effect on the interference.

At a further meeting in Moscow (June 1993), the Space Forces recognized the illegality of their transmissions and agreed to move their operating frequencies away from the 1610.6–1613.8 MHz radio astronomy band. A provisional agreement was signed, and finalized November 4, 1993. As a result, all GLONASS satellite transmissions will be out of the band by the year 2007.

Was this a hollow victory for radio astronomy? Did the emptying of the radio astronomy band by GLONASS satellites open the door to allow Motorola IRIDIUM satellites to move in? Out of the frying pan. . .

10.4 IRIDIUM Satellites

The fight with Motorola Corporation regarding its IRIDIUM satellites began in 1991 at CCIR meetings in Geneva, where the spurious and unwanted emissions from the satellites were ill defined but recognized as threatening. (The danger posed by IRIDIUM is discussed by Abbott 1996 and Ponsonby 1996.) The name IRIDIUM came from the original plan to have 77 low-flying satellites: 77 electrons orbit the iridium nucleus. Later Motorola reduced the proposal to 66 satellites (but the company has not yet renamed the system DYSPROSIUM).

"Negotiations" with Motorola Corporation to resolve the dilemma continued. Some of the participating scientists were surprised by the dictatorial style of the would-be satellite operators. The Russian Space Forces were more pliable.

The U.S. National Radio Astronomy Observatory signed a Memorandum of Understanding with IRIDIUM in June 1994. All other observatories reacted with horror, and adopted a strong defensive position behind the IUCAF banner. Later, in March 1998, Arecibo Observatory signed an MOU with IRIDIUM on much better terms than those accepted by NRAO.

Outside the U.S. the negotiations with Motorola are tougher. Australia has signed an agreement with Motorola allowing use of IRIDIUM mobiles under the condition that "the licensee must not cause harmful interference to Australian radioastronomy services." The agreement is to be reviewed after five years, at which time "IRIDIUM will be expected to demonstrate . . . that it has reached agreement with the Australian Radio Astronomy Service on the steps necessary to prevent harmful interference to Australian radioastronomy services." At the time of writing, negotiations with Motorola about IRIDIUM continue in Canada and India, as well as with a bloc of European countries.

10.5 Broadcasting Satellites

After WARC-1971 Graham Smith had alerted radio astronomers to the threat from broadcasting satellites adjacent to the RA band at 2700 MHz. Later, WARC-1988 authorized broadcasting satellites near 12 GHz.

On May 9, 1991, Masaki Morimoto alerted IUCAF to Japanese plans to license a broadcasting satellite at 22.6 GHz, using a bandwidth of 120 MHz. IUCAF sprang into action. The 22.21–22.5 GHz band is a primary allocation to space research, radio astronomy and earth exploration. The band contains an important transition of water vapor. The Japanese plan would obviously generate harmful band-edge interference to these passive services.

The Japanese proposal had to go through ITU registration procedures (so-called "Article 14" procedures). IUCAF organized protests by eight countries in the Asia-Pacific region, and the ITU registration failed to gain approval—a close shave for the passive services. More steps to protect the water-vapor band were taken at WARC-1992.

11. ADVERSE ENVIRONMENTAL IMPACTS ON ASTRONOMY

In July 1992 an IAU/ICSU/UNESCO Exposition was held at UNESCO Headquarters in Paris to publicize adverse environmental impacts on astronomy. The target audiences were government representatives, science writers and the public. The case for radio astronomy was made by Marcus Price, member of IUCAF and chairman of CORF. The exposition produced an excellent book: *The Vanishing Universe—Adverse Environmental Impacts on Astronomy* (McNally 1994). The book is aimed at scientists and the scientifically curious public.

The 1992 Exposition was a follow-up to IAU Colloquium 112 (Crawford 1991) which addressed light pollution, radio interference and space debris. At the 1992 Exposition, UNESCO was exploring the possibility of designating a few selected observatories as World Heritage sites. Nothing has yet come of this.

12. WORLD RADIO CONFERENCES 1993, 1995, 1997

From 1993, ITU World Radio Conferences (now called WRCs) are held every two years, with preparatory meetings every two months. How can the members of IUCAF cope with the flood of proposals, with the mountains of paper? Can they combine that responsibility with productive research activities in radio astronomy?

There is a contrast with the situation in the 1980s, when there were WARCs in 1983, 1985, 1987, and 1988 with little or no IUCAF participation. IUCAF has been very active in the 1993, 1995 and 1997 WRCs, and is busy preparing for the issues to be discussed at WRC 2000. The WRC agenda items relating to passive scientific use of the spectrum can be found at the IUCAF Web site, http://www.nfra.nl/iucaf.

12.1 WRC-1993

There was an unexpected German proposal at WRC-1993 that was very threatening to radio astronomy. The proposal had come up between meetings of CRAF, so European astronomers had not discussed it. At the last moment, IUCAF heard about it; Robinson and Baan rushed to Geneva for the opening of the WRC.

The German proposal was to throw open all the allocated radio astronomy bands for discussion at WRC-1997. Apparently the motive was to propose that radio astronomers share their allocations with other services “in view of new technology and new observation methods.” In exchange, radio astronomers could ask for access to other bands where interesting molecular lines were to be found. This suggestion was extremely naïve: radio astronomy would have been eaten alive at WRC-1997 by the greedy satellite operators.

The German proposal was not on the agenda of the other 27 European countries. When the motion was introduced at WRC-1993, it was immediately opposed by Australia and Canada, with the U.S. ready to join in. No European country spoke for or against the proposal, and it was excised from the WRC-1997 agenda. A very close shave.

The unplanned visit of Robinson and Baan to WRC-1993 had two positive benefits: *(a)* the Agreement between GLONASS and IUCAF, signed in Moscow on November 4, 1993 was distributed by the ITU to all WRC delegates in English, French, and Spanish—the three formal languages of the ITU; *(b)* IUCAF was alerted to the inadequate response of ITU-R to Recommendation 66 (WARC-1979 and WARC-1992). (See the section on WRC-1997.)

12.2 Belgian MLMS LEO Satellite

On December 3, 1993 the Belgian Administration announced through ITU the launching of a satellite in 1995 for a “micro low-earth orbit (LEO) message service” called MLMS, orbiting 800 km above the Earth. This launch was to be followed in mid-1995 by a second satellite, and two more satellites at a later date. The Belgians proposed a 400.15–401.0 MHz downlink using direct-sequence spread-spectrum modulation. They also planned an FSK telemetry downlink at 136.0–138.0 MHz.

Radio astronomers panicked, fearing harmful interference at 406.1–410 MHz and 322–328.6 MHz. But information from Paul Delogne and a paper by Delogne & van Himbeeck (1995) showed that out-of-band radiation can be carefully controlled in well-designed spread-spectrum systems. They showed that the power-spectral-density of spread-spectrum signals can be perfectly confined in a nominal bandwidth of 1.5 times the "chip rate." The techniques described are also "rather cheap."

Scary experiences with widespread out-of-band radiation from earlier spread-spectrum systems will diminish, hopefully. Cures for those less-sophisticated systems were expensive, involving radio-frequency filters on satellites.

12.3 WRC-1995

Nine radio astronomers from five countries attended WRC-1995 (Ananthakrishnan, Baan, Doubinsky, Gergely, Gorgolevsky, Roger, Ruf, Sinha, and Thompson). A delegation of this size is needed to deal with the multiple committees and working groups that process the work of the WRC. About 15 million pages of text were produced during the WRC. In established WRC tradition, many important issues remained stand-offs until very late in the conference, until the clock forced compromises to be forged.

The main topics of WRC-1995 were new allocations for the mobile satellite services and issues regarding their feeder links. Although radio astronomy was not directly on the agenda, new footnotes were inserted in the Radio Regulations to urge protection of radio astronomy bands from mobile satellite downlinks and feeder links. These footnotes specified protection of bands below 1 GHz, protection of the 4.99–5.0 GHz band from harmonic radiation, and protection of the 6.668 GHz methanol line and the 15.35–15.4 GHz band.

12.4 WRC-1997

WRC-1997 had around 1700 delegates from 140 countries. 15 radio astronomers attended, including 7 IUCAF representatives (Willem Baan, Jim Cohen, Boris Doubinsky, Tom Kuiper, Dave Morris, Masatoshi Ohishi, and Anders Winnberg). The mid-size IUCAF delegation was vocal during the WRC, playing a major role in the areas where radio astronomy needed to be protected. The technological/industrial pressures at the WRC can be seen from the size of the largest delegations: the United States (99), Japan (81), France (74), and the United Kingdom (47). IUCAF received considerable support from the delegations of Canada, India, France, The Netherlands, Sweden, the United Kingdom and the United States.

As at all WRCs, national delegates arrived in Geneva with established positions for the agenda items. The work of the WRC is to merge these into internationally acceptable conclusions. Some of the agenda items requiring IUCAF involvement were:

Earth-Looking Radar (94 GHZ) To explore the planet and profile clouds—the clash of astronomers wanting to look out and earth resources scientists wanting to look in. There had been no Earth resources allocation since WARC-1979. WRC-1997 allocated the band 94.0–94.1 GHz for use by a very limited number of cloud-profiling radar satellites. There is a need to reduce satellite transmissions when the satellites are overhead major radio astronomy sites operating at 3-mm wavelength.

Recommendation 66 (From WARC-1979 and WARC-1992) For several years an ITU-R task group had aimed to produce a set of protection levels from out-of-band and spurious signals that could be approved by WRC-1997. The task group could agree only on a compromise of "design objective" levels, which were two or three orders of magnitude too high to protect radio astronomy. WRC-1997 recognized the inability of the task group to suggest adequate protection for radio astronomy. Task Group 1/5 has therefore been set up to report to a future WRC. There has been very little progress in the 20 years since Recommendation 66 was first introduced at WARC-1979.

13. WRC 2000 AND BEYOND

The agenda for WRC-2000 contains 15 items of concern to IUCAF. The threats from allocations in and adjacent to radio astronomy bands continue to roll up, while ITU-R action on Recommendation 66 stalls. Some of the proposals for the 2000 WRC are:

High-Altitude Platforms There are proposals for 200 high-altitude balloon platforms, known as skystations, positioned 20 to 80 km above major cities and operating at frequencies adjacent to radio astronomy bands at 42.5–43.5 GHz and 48.94–49.09 GHz. Beam-forming antennas proposed for the balloon platforms will inherently generate unwanted emissions. Suppression of these emissions requires the development of new filtering techniques.

Mobile Satellite Services There will be consideration of the sharing of the 1610.6–1613.8 MHz and 1660–1660.5 MHz bands with radio astronomy. Another mobile satellite service is proposed in the band 405–406 MHz, which is likely to interfere with radio astronomy observations in the prime band 406.1–410 MHz. Another proposal is for fixed satellite transmissions at 15.43–15.63 GHz, adjacent to radio astronomy observations at 15.35–15.4 GHz.

Inmarsat An old problem will be reexamined at WRC-2000: an extension band for INMARSAT around 1600 MHz. The IUCAF Report to ICSU in 1992 discussed "sharing problems in the 1660 to 1660.5 MHz band and out-of-band interference in the 1660 to 1670 MHz band from aircraft communicating with INMARSAT satellites." The 1992 report said: "Discussions with INMARSAT on these problems have been unproductive." Nothing has changed.

Bands Above 71 GHZ There will be a major examination of the many radio astronomy allocations between 71 GHz and 285 GHz. Most of these were allocated at WARC-1979, soon after the rush of discoveries of millimeter-wave molecular lines. An IUCAF working group considered which of these bands are of high priority, and whether a new approach to sharing with active services might give radio astronomers access to other molecular lines that were not known in 1979. There would be protection zones around millimeter-wave observatories. Satellite downlinks and aeronautical operations need to be located adjacent to each other at the edge of atmospheric spectral windows. Allocations for the Earth Exploration Service (passive) will also be on the agenda at WRC-2000.

13.1 Prospects for the 2000s

The exciting prospects for radio astronomy in the next century are described by Kellerman (1997). Many imaginative and expensive facilities are planned, and the best sites for them have been carefully chosen.

But radio astronomers face hazards arising from digital radio broadcasting, high-definition TV, new mobile services using satellites, high-altitude platforms, and the information-age high-density data systems in the millimeter-wave spectral region (Baan 1996, Roth 1997). Already on the agenda for a later WRC are "Little LEO" mobile satellite "feeder links" adjacent to both edges of the hydrogen line band 1400–1427 MHz, a prime passive band. A future WRC will also need to allocate bands above 285 GHz.

Other advances in technology are just around the corner. How will radio astronomy cope with the flood? Do we have to go to the far side of the moon to find a radio quiet zone? How "quiet" can we keep the far side of the moon? (Morimoto 1993).

URSI has recommended (1996) that electromagnetic environmental impact statements be required before satellite transmission systems are authorized.

14. CONCLUSION

Galileo found in 1609 that exploration of the cosmos was opposed by the College of Cardinals. Now, on the threshold of the year 2000, the opposition comes from multinational corporations.

IUCAF members had to evolve from being starry-eyed astronomers as they encountered a world of politics, lobbying, entertainment, threats, espionage and bribery. On one occasion, an offer (in Geneva) of two million dollars in cash "to shut up" proved no match for dedication to the joys and excitement of twentieth-century astrophysics.

There is an insatiable demand for use of the radio spectrum. Private enterprise seeks the largest possible return on its investment dollar. At a 1995 meeting in Tel Aviv the meeting organizer said, "the communication people see the business, and will not be impressed by the importance of the science"—a case of greed versus curiosity. Fortunately, the spectrum is a renewable resource. As more TV and data links transfer to optical fibers, and as the demand for more bandwidth pushes data links into the infrared, perhaps pressure on the radio spectrum will ease. Also, far better use of coding systems and better data compression could lead to much more efficient use of the spectrum.

There is another approach: the national park system model, which limits the relentless exploitation of land through the establishment of large oases of land that are protected from development. Could the passive bands required by radio astronomy, space research, and earth exploration be kept in a pristine state as "national parks" in the spectrum, under the protection of UNESCO? The question was raised at the 1992 Exposition at UNESCO Headquarters (McNally 1994) and discussed further at the 1994 IAU General Assembly and 1996 URSI General Assembly. This issue needs to be followed up with ICSU and UNESCO. A good opportunity to discuss "national parks" was IAU Symposium 196, held in Vienna in July 1999 just before the third United Nations meeting, UNISPACE 3, on the peaceful uses of outer space.

We trust that UNESCO will support this proposal.

ACKNOWLEDGMENTS

In 1993 Sir Francis Graham Graham-Smith suggested the writing of a forty-year history of IUCAF, and has been most supportive. I have also received much help from Jim Cohen, Fred Horner, Willem Baan, and Emile Blum, to name but a few.

LITERATURE CITED

Abbott A. 1996. *Nature* 380:569

Argyle E, Costain CH, Dewdney PE, Galt JA, Landecker T, Roger RS. 1977. *Science* 195: 932–33

Baan WA. 1996. *ICSU Sci. Int.* 62:5–17

Bates DR, Massey HSW. 1947. *Proc. R. Soc.* A(192):1–16

Blackwell DE, Wilson R. 1962. *Q. J. R. Astron. Soc.* 3:109–14

Bodson D, Gould RG, Hagn GH, Utlaut WF. 1981. *IEEE Trans.* EMC-23:165–333

Bondi H, Christiansen WN, Gold T. 1961. *Trans. IAU* XI (B):354–55

Cheung AC, Rank DM, Townes CH, Thornton DD, Welch WJ. 1968. *Phys. Rev. Lett.* 21: 1701–5

Cheung AC, Rank DM, Townes CH, Thornton DD, Welch WJ. 1969. *Nature* 221:626–28

Clarke AC. 1961. *Harper's* 223:56–62

Crane PC. 1985. *NRAO News* 24:13

Crawford DL, ed. 1991. *Light Pollution, Radio Interference and Space Debris, Astron Soc. Pacific Conf. Ser.* 17:1–331

Dellinger JH. 1961. *URSI Info. Bull.* 128:78–79

Delogne P, van Himbeeck C. 1995. *Radio Sci. Bull.* 275:23–29

Denisse JF. 1961. *Trans. IAU* XI (B):83–87

Denisse JF, Seeger CL. 1961. *Trans. IAU* XI (B):348

Denisse JF, Lilley AE. 1961. *Trans. IAU* XI (B):349–50

Ewen HI, Purcell EM. 1951. *Nature* 168:356

Findlay JW. 1960. *URSI Proc.* XII (V):20–31

Findlay JW. 1962. *URSI Info. Bull.* 130:1–4

Findlay JW. 1976. *Trans. IAU* XVI (B):264–266

Findlay JW. 1984a. *URSI Info. Bull.* 230:10–11

Findlay JW. 1984b. *URSI Info. Bull.* 230:34–35

Findlay JW. 1988. *URSI Info. Bull.* 246:14–19

Finney J. 1959. *New York Times*, CIX (Oct.17):47

Gardner FF, Robinson BJ, Bolton JG, van Damme KJ. 1964. *Phys. Rev. Lett.* 13:3–5

Haddock FT. 1957. *URSI Proc.* XI:146–47

Horner F. 1971. *URSI Info. Bull.* 181:9–22

Horner F. 1972. *URSI Info. Bull.* 183:31–32

Horner F. 1976. *URSI Info. Bull.* 200:17–18

Horner F. 1980. *URSI Info. Bull.* 212:14–16

Howard WE. 1973. *Trans IAU* XV(B):166–67

Jansky CM. 1979. *Cosmic Search* 1(4)
Kellerman KI. 1997. *Sky Telesc.* 93(2):26–33
Kirby RC. 1978. *Telecomm. J.* 45:267–75
Kirby RC. 1989. *Telecomm. J.* 56:741–44
Kirby RC, Struzak RG. 1994. See McNally 1994, pp. 85–93
Lear J. 1959. *Sat. Rev.* 42(Oct 3):47–49
Lilley AE. 1961. *Astron. J.* 66:116–18
Lovell B, Ryle M. 1962. *Q. J. R. Astron. Soc.* 3:100–8
McNally D. 1994. *The Vanishing Universe*, Cambridge: Cambridge Univ. Press
Minnis CM. 1973. *URSI Info. Bull.* 188:16
Minnis CM. 1974. *URSI Info. Bull.* 192:11–14
Morimoto M. 1993. *Modern Radio Science*, pp. 226–29. Oxford: Oxford Univ. Press
Morrow WE. 1962. *URSI Info. Bull.* 130:5–12
Morrow WE. 1963. *URSI Info. Bull.* 138:89–99
Oort JH. 1960. *Am. Sci.* 48:160–78
Palmer P, Zuckerman B. 1969. *Ap. J. Lett.* 156:L147
Pawsey JL. 1955. *Trans. IAU* IX:563–89
Pickholz RL, Schilling DL, Milstein LB. 1982. *IEEE Trans. Commun.* 30:855–84
Piddington JH, Minnett HC. 1949. *Aust. J. Sci. Res. A* 2:63
Ponsonby J. 1991. *J. Navig.* 44:392–98
Ponsonby J. 1996. *Nature* 381:550
Rank B, Townes CH, Welch WJ. 1971. *Science* 174:1083–1107
Robinson BJ. 1965. *Sci. Am.* 211(7):26–33
Robinson BJ. 1976. *Proc. Astron. Soc. Aust.* 3:12–19
Robinson BJ. 1982. *Trans. IAU* XVIII (B):273–78
Robinson BJ. 1990. *URSI Info. Bull.* 255:103–13
Robinson BJ. 1991. *URSI Info. Bull.* 257:49–52
Robinson BJ. 1992. *URSI Info. Bull.*, 261:60–67
Robinson BJ, Whiteoak JB. 1979. *Proc. Astron. Soc. Aust.* 3:396–400
Roth J. 1997. *Sky Telesc.* 93(4):40–44
Seeger CL, Pawsey JL. 1961. *Trans. IAU* XI (B):354–55
Shain CA. 1951. *Aust. J. Sci. Res. A* 4:258–67
Smith FG. 1960. *Radio Astronomy*, p. 19. Harmondsworth, UK: Pelican
Smith FG. 1970. *Nature* 228:419
Smith FG. 1972a. *URSI Info. Bull.* 182:26–27
Smith FG. 1972b. *Nature* 239:61–62
Smith-Rose RL. 1956. *URSI Info. Bull.* 100:64–65
Smith-Rose RL. 1960. *URSI Info Bull.* 123:130–31
Smith-Rose RL. 1961. *URSI Info. Bull.* 128:76–80
Smith-Rose RL. 1962. *J. IEE.* 8:323–24
Smith-Rose RL. 1964a. *Nature* 203:7–11
Smith-Rose RL. 1964b. *URSI Info. Bull.* 142:39–52
Smith-Rose RL. 1964c. *URSI Info. Bull.* 147:41–42
Smith-Rose RL. 1969. *URSI Info. Bull.* 171:21–27
Smith-Rose RL. 1972. *URSI Proc.* XVI:84–85
Stumpers FLHM. 1989. *URSI Info. Bull.* 251:14–16
Sullivan W. 1959. *New York Times* CIX(Sept. 20):27
Thompson AR, Gergely T, Vanden Bout P. 1991. *Phys. Today* 44(11):41–49
Weinreb S, Barrett AH, Meeks ML, Henry JC. 1963. *Nature* 200:829–31
Westerhout G. 1979. *Trans. IAU* XVII(B):245–47
Wilson RW, Jefferts KB, Penzias AA. 1970. *Astrophys. J. Lett.* 161:L43
Woolley RvdR. 1952. *Trans IAU* VIII:610–12
Zuckerman B, Palmer P. 1974. *Annu. Rev. Astron. Astrophys.* 12:279–313