

# Assessing basic research: Reappraisal and update of an evaluation of four radio astronomy observatories \*

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This paper critically reassesses the results of a previous evaluation of the research performance of four radio astronomy observatories over the period 1969–78, completed by two of the authors in 1980. At the same time, the evaluation is updated by presenting bibliometric (publication and citation) data for the subsequent five-year period 1979–83. While application of a more developed evaluation methodology is shown not to alter significantly the conclusions arrived at in the earlier study, there is evidence that the relative research performance of the four observatories has changed significantly since 1978.

## 1. Introduction

The need perceived by science policy-makers for research evaluation techniques is today almost certainly greater than in 1980 when this journal accepted for publication the results of an assessment of the scientific performance of four large radio astronomy observatories (see Martin and Irvine [19]).<sup>1</sup> While there had been several earlier studies attempting to assess the scientific outputs from research groups and centres,<sup>2</sup> the conven-

tional wisdom at the time was that there was no alternative to relying solely upon the judgements of scientists in the field concerned for the information required to evaluate performance.

Views have since begun to change, however, as it has become evident that the mechanism of peer-review traditionally used to determine resource distribution in basic research is proving less satisfactory than in more affluent times when national science budgets were rising significantly in real terms.<sup>3</sup> The result has been a growing awareness that decision-making might usefully be informed by more systematic data on the past performance of research groups and laboratories. Funding agencies in various countries have consequently been experimenting with the application of bibliometric techniques to policy-making in science.<sup>4</sup> These experimental studies have pro-

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<sup>1</sup> Although the main paper arising from the study appeared in 1983, it had been accepted for publication in 1980.

<sup>2</sup> See, in particular, the assessment carried out by Larabi [16,17] of French space research, the study by Matheson [23] of British university chemistry departments, and the analysis by Chang and Dieks [2] of the publication output

from Dutch physics. In a more general sense, Garfield [7] and Narin [27] can be regarded as having laid the foundations for the later, more widespread use of bibliometrics in science policy.

<sup>3</sup> The problems with peer-review are discussed by Irvine and Martin [11] and by Roy [29, p. 317] who concludes that "the failures of review by peers as a way of deciding which projects and which scientists should receive grants seem to be very evident".

<sup>4</sup> The Dutch have been especially active in this area, with the Ministry of Education and Science funding a major exercise to explore the possibility of employing bibliometric indicators to monitor departmental research performance in universities – see Moed et al. [24,25]. In Britain, the Advisory Board for the Research Councils (ABRC) supported in 1983/84 a comparative study examining the relative merits of different bibliometric techniques – co-citation analysis, co-word analysis, and the use of manual scanning approaches – see Coward et al. [5], Turner [30], Crouch et al. [6], and the summary review by Healey et al. [9]. Exploratory studies have also been supported in West Germany, Spain and Australia.

duced sufficiently promising results that, notwithstanding their intrinsic limitations and the scepticism of those who continue to defend the unconditional autonomy of science, bibliometrics is now widely seen as having a potentially important role to play in science policy.<sup>5</sup>

At the time of the first radio astronomy study, it still remained to be demonstrated that research output could be measured reliably and in a manner acceptable to the scientific community itself. The main rationale behind the study was therefore to develop and test a method for evaluating the relative scientific performance of research groups working in the same field. Given the traditional stress laid by the scientific community on regulating their own affairs, it was important to show that such assessments could indeed be undertaken by “outsiders”. The reason we chose to focus on “big science” (parallel studies were also carried out of optical astronomy and electron high-energy physics, see [10] and [18]) – was because of the special problems that had become apparent. In particular, the concentration over time of research activities within ever fewer laboratories had tended to create an oligopolistic structure in which it was more difficult to locate disinterested peers able to provide balanced judgements on the merits of proposed new facilities and programmes. Furthermore, the “lumpiness” of capital investments like accelerators and telescopes meant that the costs of poor decision-making had become much higher.<sup>6</sup>

Of the two reasons for reassessing the four radio observatories focussed on in the original study, one is to examine any changes in performance that have taken place since 1979. When shown the earlier results, one observatory argued

that the ten years up to 1978 had been a particularly difficult period and that the indicators employed in the evaluation did not, therefore, give a fair reflection of its overall performance. Concern was expressed that there could be unfortunate financial consequences for the observatory if policy-makers uncritically accepted the findings. Senior observatory staff predicted that the indicators would show a significant improvement from 1979 onwards as research results were produced from a major new facility. The work described here tests this prediction over the subsequent five-year period.

Second, the methodological approach used by us to evaluate research performance has been refined as further studies have been undertaken – for example, of the past performance and future prospects of the particle accelerators at CERN, the joint European laboratory at Geneva, compared with similar high-energy physics facilities around the world (see [12], [20], [21]). Five years on, the deficiencies of the approach used in the original study are now all too evident, and several authors have published technical and conceptual critiques.<sup>7</sup> From both a methodological and policy point of view, therefore, it is important to ascertain whether a more developed approach leads to significantly different conclusions on the comparative performance of the four observatories over the period 1969–78.

In carrying out this reappraisal, we have reason to think back to events around 1980 when we were beginning to circulate preliminary drafts of the results from the radio astronomy study. At the time, Yvan Fabian, then Director of the Science and Technology Indicators Unit at OECD, was instrumental in giving us the opportunity to present our somewhat controversial findings to the international science policy community. His view was that an urgent priority for science policy research was to develop output indicators analogous to the input indicators compiled by his unit at OECD. Understanding only too well the technical, conceptual and political problems associated with such an endeavour, he was able to accept our still unrefined approach to research evaluation as

<sup>5</sup> In an authoritative review of non-economic approaches to evaluating the outputs from science carried out for the US Office of Technology Assessment, Chubin [3] concludes that bibliometric techniques are now sufficient developed to be used as a policy tool by administrators in funding agencies. Also of note is the fact that institutional research assessment was a central concern in the 1985/86 hearings of the Science Policy Task Force of the US Congressional House Committee on Science and Technology.

<sup>6</sup> One of the most visible failures has been the Brookhaven Isabelle accelerator, construction of which was terminated in 1984 after expenditure of some \$200 million had already been incurred [28].

<sup>7</sup> See, in particular, Gillmor [8] but also Bud [1], Collins [4], Krige and Pestre [15], and Moed and van Raan [26], along with our responses ([13], and [22]).

a prototype and to lend his support for its further development. Without such backing at that time, we would have found it more difficult both to gain wider acceptance of our approach in the science policy community and to secure the funds to extend the programme on research evaluation. This support and guidance continued right up to Yvan's untimely death in 1985. Like many of our colleagues, we shall much miss the enthusiastic and informed encouragement to explore new research directions that he so effectively provided.

## 2. Methodology

The methodological approach used in this new study is derived from that employed originally (see Martin and Irvine [19]), but there are several differences which are described below. Common to both is the application of a range of bibliometric indicators (numbers of scientific papers, total citations to recent papers, citations per paper, and numbers of highly cited papers), each reflecting a different facet of research performance (for example, output, productivity and scientific impact), to the four observatories. The results are then compared with "peer-rankings" obtained (in the original study) by inviting a large sample of scientists in the field to rank the observatories in order according to their relative contributions to observational radio astronomy. The observatories are the Nuffield Radio Astronomy Laboratories at Jodrell Bank, the Mullard Radio Astronomy Observatory at Cambridge, the Max-Planck-Institut für Radioastronomie (MPI) (whose main telescope is at Effelsberg near Bonn<sup>8</sup>), and the Netherlands Foundation for Radio Astronomy (NFRA) with its facilities at Westerbork and Dwingeloo. Whereas the earlier study covered the decade from 1969–78, here the period has been extended by five years up to the end of 1983.

As noted above, since completing our original study in 1980, a number of problems have become apparent with the methodological approach employed. Three are of particular importance:

- (1) the unit of analysis on which the study focussed (the research "centre") was probably not the most appropriate or at least was not adequately specified;
- (2) there was no proper breakdown of publication output (between, for example, theoretical, observational, instrumental and review papers);
- (3) the criteria for deciding which papers should be included or excluded were not sufficiently clear.<sup>9</sup>

As regards the first and second of these problems, it became clear during two closely associated studies of optical telescopes [10] and electron accelerators [18] that the primary unit of analysis in evaluations of "big science" should normally be the experimental or observational research facility, and not the research "centre" as such. The *raison d'être* of big science "centres" is to operate centralized research facilities which, because of their expense and technical sophistication, cannot be provided individually to all academic research groups working in the area. There are several different models for operating such "centres", one extreme in radio astronomy consisting of the users of each facility also being based at the observatory (this is predominantly the case at Cambridge, Jodrell Bank, and MPI if the closely associated Department of Radio Astronomy at the University of Bonn is included). The other extreme is the operation of central facilities by a small group of core staff with most research being undertaken by a dispersed user-community (this is closer to the mode of operation of NFRA).

Because there are these different types of "centre", comparisons can in general only be made between the observational results arising from the *telescopes* operated by each observatory, irrespective of whether they are reported in publications produced by in-house researchers or outside users. In addition, it means that it is not in most cases appropriate to place significant weight on theoretical contributions. This is partly because the inclusion of such contributions would bias the results against those "centres" operating on a model where

<sup>8</sup> The MPI publication list also contains a few papers reporting observations made on radio telescopes at Bochum and Stockert. However, these amount to less than 3 percent of the total and the number has been negligible since 1974.

<sup>9</sup> Although we were ourselves already aware of many of the limitations in the original study, we are grateful to C.S. Gillmor [8] for his critical comments and for encouraging us to look more closely at the various problems.

such research is devolved within the wider academic community, and, conversely, towards those to which a large theory group is attached. It also reflects the fact that, compared with experimental research, theoretical work is relatively inexpensive and can in principle be carried out almost anywhere since it is normally based on already available observational results. We were not fully aware of this problem in the earlier study (mainly because most of the theoretical papers from each observatory included at least some secondary analysis of data from their telescopes) and made no attempt to distinguish the smaller number of theoretical publications from the larger number reporting observational results.

In what follows, we concentrate primarily on the observational contributions to (galactic and extragalactic) radio astronomy arising from research undertaken on the telescopes operated by the four laboratories, although for background and comparative purposes we also provide an analysis of the theoretical output of the researchers at, or associated with, each observatory. We are not concerned here with the small number of instrumental articles reporting technical developments at each observatory since these generally constitute contributions to the engineering and applied science literature, and are not strictly comparable to papers reporting scientific results.

The way we have tackled the third problem is by employing a much stricter set of criteria for deciding which papers to include. As in the original study, the starting point for constructing counts of papers (and hence the other output indicators) was a set of publication lists provided by each observatory.<sup>10</sup> The first step was to distinguish papers appearing in learned journals (that is,

refereed journals with an international readership) from all other publications (books, conference proceedings, articles in “popular science journals”, in-house reports and theses), with the latter being excluded from further analysis. This is a somewhat different approach from the original radio astronomy study where papers published in conference proceedings were included,<sup>11</sup> but it is consistent with all our subsequent evaluations of “big science” facilities. The justification for excluding conference papers is that most are subsequently published in revised form as journal articles and to include them would introduce a significant element of double-counting. As before, books and chapters in edited books were not included on the grounds that they constitute “secondary literature” – that is, they tend not to report original research findings but to draw upon results contained in the primary literature of journal articles. “Popular science” journals (for example, *Sky and Telescope*, *Sterne und Weltraum*) were identified for us by astronomers and observatory librarians, and articles in them excluded since, like books, they do not generally report new (i.e. previously unpublished) research results. Finally, in-house reports and theses were excluded since they are in general not circulated widely and any important findings they contain are normally published elsewhere.

Each of the articles published in learned journals was then scanned (and, if necessary, read in detail) by one of the authors with a postgraduate training in astronomy in order that they could be classified into one of the following categories:

- (1) observational radio astronomy – this was defined as any paper presenting previously unpublished observational data on astronomical objects outside the solar system (strictly the more cumbersome term, “observational galactic and extragalactic radio astronomy” should be used to describe this category of papers);
- (2) observations within the solar system – any paper presenting previously unpublished data

<sup>10</sup> This procedure depends for its accuracy on the extent to which observatories comprehensively record publications arising from use of their telescopes. With Cambridge and Jodrell Bank, few problems are likely to occur since the publication output is mostly in-house, while NFRA operates fairly strict procedures requiring users to report publications arising from all observational time allocated. Some papers will, nevertheless, be missed (see note 13 below), and it would have been preferable to compile the lists of publications by scanning the main journals for the subject, as was done for high-energy physics in our study of CERN [20]. Time and resource constraints prevented us from adopting this alternative procedure here.

<sup>11</sup> This results in substantially different numbers of papers for NFRA and MPI, the publication lists of which include many conference papers. The figures reported below are, therefore, not directly comparable with those contained in the original study.

on objects within the solar system (since the researchers interviewed by us were asked in the peer-ranking exercise to compare observatories in terms of the contributions of their telescopes to *radio astronomy*, it was decided to separate observational work in the areas of solar and planetary physics, and geophysics, including ionospheric physics, from that in galactic and extragalactic radio astronomy);<sup>12</sup>

- (3) theoretical astronomy – any article containing a theoretical analysis either of the nature of astronomical objects or, of previously published observational results and their interpretation, but without itself presenting any new observational data; since this is a rather broad use of the term “theoretical”, it might be argued that it would be better to describe these as “theoretical and/or interpretive” papers, but we have elected to continue using the less cumbersome term “theoretical” in what follows;
- (4) instrumental – any article reporting experimental, theoretical or other details relating to instruments and devices used to obtain astronomical observations;
- (5) laboratory experiments – any article containing the results of a laboratory experiment of relevance to astronomy (for example, the measurement of certain atomic and molecular spectra);
- (6) review articles – a collation of previously published theoretical or observational findings;
- (7) other articles – this category consists of a small number of publications (less than 0.5%) to which we were unable to obtain access (for example, because they appeared in non-European journals with restricted circulation) and which could not therefore be classified into one of the above categories.

<sup>12</sup> For the four observatories evaluated here, the numbers of papers reporting observations of objects or phenomena within the solar system are so small that it makes little practical difference to the overall assessment whether they are included or not. However, this is not true in the case of two of the observatories included within the peer-ranking exercise, Nançay and Arecibo, which devote a substantial portion of their observational work to the solar system. As a result, the peer-rankings for these two observatories cannot be taken as reflecting judgments about all the observational results arising from their telescopes, but only those on galactic and extragalactic objects (see [13]).

It should be noted that classification was undertaken according to the above priority order (1) down to (6) so that an article reporting both observational radio astronomy and instrumental results, for example, was categorized as “observational radio astronomy”.

The final stage in analysing the publications was that all the observational radio astronomy papers were scanned in order to establish which telescope (or telescopes) had been used to obtain the results reported. Papers based on observations derived from telescopes operated by centres other than those focussed upon here (for example, a US telescope used by, say, a Jodrell Bank astronomer while on sabbatical leave) were excluded on the grounds that they did not constitute contributions from the research facilities at the four observatories. Where telescopes at two or more observatories were involved (a pattern of usage which has become more common with the spread of very long baseline interferometry, VLBI), papers were credited in full to each of the contributing facilities.<sup>13</sup>

<sup>13</sup> A radio astronomer who read an earlier draft of this article pointed out that in some cases foreign authors of a paper reporting VLBI observations derived from several telescopes, including the one at Effelsberg, may not notify MPI of its publication. We subsequently investigated the extent to which MPI publication lists are incomplete by comparing them with a bibliography of VLBI papers compiled by Professor M.F. Cohen [31] of Owens Valley Radio Observatory, California Institute of Technology. For 1979 and 1980, this yielded 7 publications involving the Effelsberg telescope missing from the MPI lists. This compares with a total of 95 observational radio astronomy papers which are contained in the lists for 1979 and 1980, and suggests the MPI data are reasonably comprehensive at least up to 1980. (The possibility that the number of “missing” papers may have grown since then could not, unfortunately, be investigated since the VLBI bibliography only covered the period up to 1980.) In the event that VLBI papers grow to constitute a significant part of the output of radio telescopes, it will be necessary to adopt a fractional system of crediting papers to the facilities on which the research is carried out. The approach used in this paper of crediting publications in full to each contributing telescope breaks down where multi-observatory papers constitute more than a minor part of total output. The reason is that a VLBI publication produced, for example, on seven telescopes by US astronomers obtaining remote access to the MPI, is arguably not comparable to a paper reporting observations made exclusively on the Effelsberg facility. As a result, the exclusion of small numbers of VLBI papers which should perhaps be fractionally credited is less of a problem than at first appears to be the case.

Once the articles contained in the publication lists provided by the four observatories had been categorized, a bibliometric analysis was carried out to produce the same indicators of scientific performance as in the earlier study. Citation data for each article were compiled manually by scanning the relevant annual volumes of the *Science Citation Index (SCI)* for the period 1969–83. This yielded a new set of citation statistics which could be used to check the figures compiled previously. Analysis of the two data sets showed few inconsistencies between the records for the individual papers over the period up to 1978 other than minor clerical errors or oversights (for example, failure to include a citation attributed in the *SCI* under a misspelt name). The scanning was undertaken by two different analysts so as to permit testing of the reliability of the citation data. It was discovered during this work that the procedures used in the earlier study to identify highly cited papers had failed to pick up a small number that briefly attained marginally more citations than the lowest threshold for inclusion (12 citations in a single annual volume of the *SCI*) after previously making little apparent impact. The improved procedure for identifying highly cited papers is described in the methodological appendix.

Let us now examine the results of our re-evaluation and update of the contributions to observational radio astronomy made using telescopes operated by the four observatories.

### 3. Contributions to observational radio astronomy

#### 3.1. The period 1969–78

The results of the analysis of observational (galactic and extragalactic) radio astronomy papers published in learned journals are summarized in table 1. The upper set of figures in the table, the biennial publication totals, reveals broadly similar trends for each observatory over the period 1969–78 to those contained in table 6 of Martin and Irvine [19]. For example, the Cambridge figures exhibit the same “dip” in the early 1970s before recovering to reach a maximum at the end of the decade, while the Jodrell Bank figures for 1970 and 1972 are somewhat higher than those in 1976 and 1978. As for NFRA and MPI, the telescopes of both observatories accounted for a rapidly increasing number of publications in the period up to 1978 as new research facilities came into operation and astronomers became more experienced in using them. In terms of the overall positions of the four observatories, the figures in the penultimate column on the average annual publication rate over the ten years in question show that NFRA was responsible for most papers (23 per annum), and that there was little significant difference between Cambridge (16), MPI (15) and Jodrell Bank (14). Thus, the effect of excluding from consideration conference papers and treating observational radio astronomy articles in

Table 1  
Bibliometric analysis of journal articles on observational radio astronomy

		1970	1972	1974	1976	1978	1980	1982	1983	Annual average 1969–78	Annual average 1979–83
Number of journal articles published in last 2 years	Cambridge	33	25	25	35	39	42	24	14	16	15
	Jodrell Bank	30	34	28	26	25	33	37	39	14	18
	NFRA	10	36	43	63	75	77	66	65	23	35
	MPI	3	3	30	45	67	95	95	74	15	45
Number of citations to articles published in last 4 years <sup>a</sup>	Cambridge	–	250	150	220	250	220	180	150	210	180
	Jodrell Bank	–	140	150	140	140	140	140	170	140	150
	NFRA	–	120	220	330	370	380	250	300	260	310
	MPI	–	–	50	140	260	440	370	340	110	380
Citations per paper for publications of last 4 years	Cambridge	–	4.2	2.9	3.6	3.4	2.7	2.7	2.8	3.5	2.7
	Jodrell Bank	–	2.2	2.4	2.7	2.8	2.5	2.0	2.3	2.5	2.2
	NFRA	–	2.5	2.8	3.1	2.7	2.5	1.8	2.2	2.8	2.2
	MPI	–	–	1.4	1.9	2.3	2.7	1.9	1.8	2.0	2.1

<sup>a</sup> All the citation figures have been rounded to the nearest 10.

Table 2  
Numbers of observational radio astronomy publications relative to staffing and funding levels in 1978

	Average annual publication rate 1978–80 <sup>a</sup>	Effective no. of researchers <sup>b</sup>	Annual running costs <sup>c</sup> (£m)	No. of papers per researcher	Average cost per paper (£k)
Cambridge	21.3	28	0.6	0.8	30
Jodrell Bank	14.7	34	0.9	0.4	60
NFRA	37.3	~ 47	2.6	0.8	70
MPI	45.7	~ 73	3.7	0.6	80

<sup>a</sup> The average over a three-year period has been used to correct essentially random fluctuations in the yearly totals. The period 1978 to 1980 has been chosen to allow for the delay (typically a year or so) between completing an observational study and publication.

<sup>b</sup> Taken from table 2 in Martin and Irvine [19, p. 78].

<sup>c</sup> Taken from table 3 in *ibid.* [19, p. 79].

isolation from theoretical and other work is to narrow considerably the gap between the most and least prolific observatories compared with our earlier study.

A similar effect can be seen in table 2 with the figures for 1978 relating to productivity – that is, publication output relative to staffing and funding levels. Although, as before, Cambridge produced the most papers per researcher (along with NFRA) at the lowest cost (£30K), the differences between the four observatories are somewhat smaller than evident in the equivalent figures in table 7 of Martin and Irvine [19, p. 81].

Table 1 also contains the results of the citation analysis. Over the period 1969–78, as in the original study NFRA and Cambridge emerged as the most successful in terms of the impact of their research with an annual average of 260 and 210 citations respectively to “recent” observational articles (i.e. articles published in the preceding four years). Although MPI recorded the lowest average figure (110 citations), this is explained to some extent by its late entry into the field. (The first observations on the Effelsberg telescope were only made in 1972, and it took another three or four years before a fully productive observing schedule was established.) By 1978, the German observatory had moved significantly ahead of Jodrell Bank (260 citations compared with 140) and indeed had overhauled Cambridge (which earned 250 citations in that year). As for the figures on average citations per paper, the overall picture is broadly similar to that obtained previously, with Cambridge achieving the highest score (an average of 3.5 over the ten years), followed by

NFRA (2.8) and Jodrell Bank (2.5), both of which were some way ahead of MPI (2.0).

The figures on highly cited papers for the period 1969–78, employed as an indicator of research results with especially high impact,<sup>14</sup> are shown separately in table 3. It should be noted that the data refer to observational articles published in the ten years which were highly cited *in any year up to 1983*. As a result, they include a number of papers published in the latter part of the period up to 1978 which subsequently became highly cited between 1979–83, and cannot therefore be compared directly with the figures in table 12 of Martin and Irvine [19, p. 83].<sup>15</sup> In terms of papers cited 20 or more times in a year, it can be seen from table 3 that Cambridge was by far the most successful over 1969–78 with 8 such papers, followed by NFRA with 3 and MPI with 1, while Jodrell Bank had none. With a threshold of 15 or more citations in a year, a similar pattern emerges. However, at a lower threshold of 12 (which may not be sufficiently high to discriminate papers reporting major advances from those constituting incremental additions to the field), the differences between the observatories are less pronounced. A comparison with our earlier results (see table 12 in

<sup>14</sup> For example, the Cambridge figure for highly cited papers in table 3 includes the discovery of pulsars in 1973, which was the most cited paper from all four observatories over the entire period 1969–78.

<sup>15</sup> In addition, as noted earlier, the procedure used to identify highly cited papers missed a small number cited just above the threshold of 12 for a single year only.

Table 3  
Highly cited papers on observational radio astronomy

		1969–78		1979–83	
		No. of papers	No. of times papers were highly cited	No. of papers	No. of times papers were highly cited <sup>a</sup>
Cited 12 or more times in a year	Cambridge	22	73	0	0
	Jodrell Bank	10	16	2 <sup>b</sup>	4
	NFRA	23	41	5	6
	MPI	9	20	6	6
Cited 15 or more times in a year	Cambridge	15	46	0	0
	Jodrell Bank	2	2	1	2
	NFRA	7	14	4	5
	MPI	6	13	1	1
Cited 20 or more times in a year	Cambridge	8	22	0	0
	Jodrell Bank	0	0	1	2
	NFRA	3	5	1	1
	MPI	1	3	1	1

<sup>a</sup> These figures are much smaller than those for the period 1969–78 partly because recent papers have had far less time to become highly cited (citations were scanned in the *Science Citation Index* up to the end of 1983, whereas in the original study they were scanned only to 1978).

<sup>b</sup> This includes one paper initially excluded on the grounds that it did not appear to report new data obtained on a Jodrell Bank telescope. It was subsequently included after we had been assured that it did actually meet our criteria for inclusion.

[19, p. 83]) shows a close similarity for the figures on more highly cited papers (cited above a threshold of 15 and 20). The main difference is again a narrowing of the gap, especially for papers achieving the lower level of 12 citations, between the observatories making the greatest and least impact according to this particular indicator.

The overall performance of the four observatories as regards the output, productivity and impact of their work in observational radio astronomy published between 1969 and 1978 is summarized in table 4, which shows their relative positions in terms of each of the main indicators. Thus, NFRA, which produced most papers, is ranked first for this indicator, followed by Cambridge, MPI and Jodrell Bank, all with approximately the same average annual publication rate (within the limits of reliability that can be attached to the data reported here). The table also shows (in brackets) the relative positions for each indicator accorded in the original study. A comparison between the two sets of results reveals a few small differences – for example, in the case of the relative position of MPI for the indicator based on annual publication rate.

However, the overall picture yielded by the two studies of the comparative scientific performance

Table 4  
Relative positions of the four observatories in terms of their contributions to observational radio astronomy, 1969–78<sup>a</sup>

	Cam-bridge	Jodrell Bank	NFRA	MPI
Annual average publication rate <sup>b</sup>	3 <sup>f</sup> (3)	3 <sup>f</sup> (4)	1 (1.5) <sup>g</sup>	3 <sup>f</sup> (1.5) <sup>g</sup>
“Productivity” in 1978 <sup>c</sup>	1 (1)	3.5 <sup>h</sup> (4)	2 (2)	3.5 <sup>h</sup> (3)
Average number of citations to work of last 4 years <sup>b</sup>	2 (2.5) <sup>j</sup>	3 (4)	1 (1)	4 (2.5) <sup>j</sup>
Average citations per paper <sup>b</sup>	1 (1)	3 (2)	2 (3)	4 (4)
Numbers of highly cited papers <sup>d</sup>	1 (1)	4 (3.5) <sup>h</sup>	2 (2)	3 (3.5) <sup>h</sup>
“Average” position for above 5 indicators <sup>e</sup>	1.6 (1.7)	3.3 (3.5)	1.6 (1.9)	3.5 (2.9)

<sup>a</sup> Bracketed figures show the relative positions based on the results of the original study.

<sup>b</sup> Based on the figures in the penultimate column of table 1.

<sup>c</sup> Based on the figures in table 2.

<sup>d</sup> Based on the figures in table 3 for  $n \geq 15$  and 20.

<sup>e</sup> See footnote 16.

<sup>f</sup> Denotes equal second position (equal with two others).

<sup>g</sup> Denotes equal first position.

<sup>h</sup> Denotes equal third position.

<sup>j</sup> Denotes equal second position (with one other).

of the four observatories is essentially similar, as can be seen if one calculates the “average” position of each observatory for the five indicators<sup>16</sup> (see the bottom row of table 4). These indicators are in close agreement with the results of the earlier peer-ranking exercise reported in Martin and Irvine (see table 13 and the accompanying discussion in [19, pp. 84–86]). This involved inviting approximately 60 astronomers at the four centres to rank 9 major observatories on the basis of the contributions to radio astronomy made by users of their observational facilities over the period 1969–78. Cambridge, with an average ranking of 2.2, was perceived by those interviewed to have been the world-leader over this period, followed closely by NFRA (ranked 2.8). They were both placed appreciably ahead of MPI (5.1), which was judged to have been slightly more successful than Jodrell Bank (6.0).<sup>17</sup> In view of this consistency between the results yielded by the various bibliometric indicators and the peer-rankings, we conclude that the technical defects in our first application of the “method of converging partial indicators” were not of sufficient magnitude to distort appreciably the findings on the relative contributions to radio astronomy of telescopes at the four observatories between 1969 and 1978.

### 3.2. *The period 1979–83*

Given that Cambridge was probably the world-leader in radio astronomy over the earlier ten-year period, it is of some interest at least to British policy-makers to see whether this dominance has continued. There is growing evidence of an overall decline in Britain’s world standing as a scientific nation (see Irvine et al. [14]), and radio astronomy is a field where the country’s lead was previously undisputed. Also of interest is the im-

pact that the major investment in the new Jodrell Bank facility (the Multi-Element Radio-Linked Interferometer Network, MERLIN) has had on the observatory’s standing in relation both to Cambridge (which has had no similar major capital investment in its own facilities since the early 1970s), and to the other two European observatories.

The various bibliometric indicators for contributions to observational radio astronomy associated with telescopes at the four observatories over the period 1979–83 are given in table 1, above. Perhaps the most interesting feature of the table is the marked change in relative positions that has taken place since 1978. In terms of output of journal articles, MPI produced more than the three other observatories (an average of 45 per annum between 1979 and 1983), a considerable improvement on its record over the previous period. NFRA also registered an appreciable increase (from 23 to 35 per annum), while Jodrell Bank’s output rose by a quarter (from 14 to 18) to a level slightly higher in 1981–83 than its peak in the previous period (in 1971–72). However, probably the most significant change is that for Cambridge, with the figure for 1982–83 representing a halving in published output compared to 1969–78 (7 as opposed to 16 per annum) and only a third of the peak recorded in 1979–80 (21 per annum).

A similar pattern can be seen from table 1 in the figures on citations to articles published in previous four-year periods, with MPI registering the largest increase (from an average of 110 a year over 1969–78 to 380 for 1979–83) and NFRA a somewhat smaller rise (from 260 to 310 citations a year). There has been little change in Jodrell Bank’s performance in terms of this indicator (although there was a slight increase in 1983), while Cambridge has suffered a pronounced decline the 1983 figure of 150 citations representing a 40 percent reduction on the peak value of 250 recorded in 1978. The decline in total citations made to Cambridge’s published work is partly the result of researchers having published fewer journal articles, and partly a consequence of observations from telescopes at the centre apparently making less impact on the scientific community. The latter can be seen from the figures on average citations per paper in table 1, with observational papers from Cambridge telescopes achieving an average of 2.7 citations per paper in 1979–83, compared with 3.5

<sup>16</sup> This is obviously a somewhat crude procedure because it implicitly involves weighting each indicator equally, whereas many scientists would argue that certain indicators – in particular, the one based on highly cited papers – are more important or that others should be included.

<sup>17</sup> Although MPI and Jodrell Bank are ranked equally in terms of the bibliometric indicators in the present study, it can be argued that the productivity figures are biased against the German observatory since it was not fully operational in the earlier part of the period 1969–78. If allowance is made for this, MPI would then be ranked ahead of Jodrell Bank, in line with the judgements of the astronomers interviewed.

in the previous ten years. However, this is still about 25 percent higher than the corresponding figure for the other three observatories.

Perhaps the sharpest fall in the performance of Cambridge appears in the figures on highly cited papers in table 3, above. Even at the lowest threshold considered of 12 citations in a year, Cambridge has produced no papers making a major impact on the scientific community, compared with 2 by Jodrell Bank, 5 by NFRA and 6 by MPI. This result, together with those for the other indicators, is summarized in table 5, which gives the relative positions of the four observatories in terms of the contributions of their telescopes to observational radio astronomy over the five years up to the end of 1983. A comparison between these rankings and those in table 4 shows that the main changes between the periods 1969–78 and 1979–83 are the decline in Cambridge's position and the improvement in that of MPI. The figures in table 5 suggest that MPI and NFRA have apparently made the largest contributions of the four laboratories to observational radioastronomy since 1979, while there is little difference between the overall contributions of Cambridge and Jodrell Bank, the higher average impact of Cambridge papers offsetting the greater Jodrell Bank output.

While these bibliometric indicators throw some light on the relative performance of the four

European observatories over the period 1979–83, they do not enable us to come to any firm conclusions about their overall world-standing since we have been unable (for reasons of limited resources and time) to compile equivalent bibliometric data for the facilities at other major centres or to update the peer-ranking exercise carried out previously. It may well be, for example, that the US National Radio Astronomy Observatory (placed third in the original peer-ranking exercise) has wrested the lead from Europe since the completion in 1980 of the Very Large Array (VLA), the major new interferometer at Socorro in New Mexico. Whatever the case, one conclusion that can probably be drawn is that Britain seems to have lost its former pre-eminent position in observational radio astronomy, the capital investment in MERLIN at Jodrell Bank having apparently not enabled the observatory to step into the position previously occupied by Cambridge at least in the period up to the end of 1983.

#### 4. Contributions to theoretical radio astronomy

Apart from the effect of excluding conference papers, the main factor underlying the differences between the figures reported above and those in Martin and Irvine [19] is that theoretical papers were previously included in the analysis. As argued earlier, the existence of different models for the operation of radio astronomy central facilities means that the primary focus for assessment should be the observational contributions made by users, both in-house and external, of the telescopes operated by each observatory. However, since theoretical papers were originally included, and since such papers constitute the second largest category of publications from the four observatories in the study,<sup>18</sup> it is worth briefly considering the contributions made in this field. It should, however, be borne in mind that the findings are not necessarily of direct relevance to an evaluation of observatory performance because, for example,

<sup>18</sup> There are relatively few "solar-system observations", "instrumentational" and "laboratory experiment" papers in the publication lists for the four observatories. The only other major category of papers consists of those reporting observational results produced using telescopes at observatories other than the four focused on here.

Table 5  
Relative positions of the four observatories in terms of their contributions to observational radio astronomy, 1979–83

	Cambridge	Jodrell Bank	NFRA	MPI
Annual average publication rate <sup>a</sup>	4	3	2	1
Average number of citations to work of last 4 years <sup>a</sup>	3	4	2	1
Average citations per paper <sup>a</sup>	1	3 <sup>c</sup>	3 <sup>c</sup>	3 <sup>c</sup>
Numbers of highly cited papers <sup>b</sup>	4	3	1	2
"Average" position for above 4 indicators <sup>d</sup>	3.0	3.2	2.0	1.8

<sup>a</sup> Based on the figures in the last column of table 1.

<sup>b</sup> Based on the figures in table 3.

<sup>c</sup> Denotes equal second position (equal with two others).

<sup>d</sup> See footnote 16.

the NFRA model of a central facility with a largely external user-community and associated theorists differs from that of Cambridge, Jodrell Bank and MPI, where the theoretical output is produced by resident staff.

Table 6 contains the results of our bibliometric analysis of theoretical astronomy articles published in learned journals. Over the ten years up to 1978, Cambridge and MPI researchers produced most papers (an average of 11 per annum), well ahead of NFRA (6) and Jodrell Bank (4). However, the Cambridge papers over this period appear to have made the greatest overall impact, averaging 110 citations a year to work published in the previous four years, significantly more than MPI and NFRA (which averaged 80 and 70 citations respectively) and well ahead of Jodrell Bank (40 citations). The reason for this is that, although MPI published a large number of theoretical papers, these apparently had less impact, averaging only 1.8 citations per paper compared with 2.3 or more for the other three observatories. Cambridge was also the most successful in this earlier period in terms of theoretical papers achieving a particularly high impact. Table 7 shows that it produced 4 papers cited 20 or more times in a year, compared with just 1 each from NFRA and MPI and none from Jodrell Bank. At a threshold of 15 citations in a year, Cambridge recorded a figure of 6 papers, twice as many as the next most

successful observatory, MPI, while NFRA produced 2 and Jodrell Bank none.

As with observational radio astronomy, there has apparently been a major shift in overall contributions to theoretical astronomy since 1978. Cambridge has again suffered a particularly pronounced decline; as can be seen from table 6 below, its annual output of papers fell by half between 1979–80 and 1982–83. Moreover, the impact of its theoretical work declined even more sharply, the number of citations to papers published in the last four years dropping by over a half between 1980 and 1982 (from 180 to 80) and halving again in 1983 (to 40). After earning by far the highest number of citations per paper in 1978 and 1980, Cambridge theoretical papers were by 1983 receiving the lowest number (1.5) among the four observatories. Only in terms of highly cited papers (see table 7) has Cambridge continued to prove reasonably successful, with one paper cited 20 or more times (on four occasions) compared with none from Jodrell Bank and MPI. Overall, the most successful as regards highly cited papers was NFRA which, like Cambridge, produced one paper cited 20 or more times, but a larger number cited at thresholds of 12 and 15.

The relative performance of the four observatories in terms of the various indicators of contributions to theoretical astronomy over the periods 1969–78 and 1979–83 is summarized in table 8.

Table 6  
Bibliometric analysis of journal articles on theoretical astronomy

		1970	1972	1974	1976	1978	1980	1982	1983	Annual average 1969–78	Annual average 1979–83
Number of journal articles published in last 2 years	Cambridge	18	22	28	17	27	18	10	9	11	6
	Jodrell Bank	8	8	10	6	7	3	4	4	4	2
	NFRA	8	15	13	10	15	34	22	24	6	13
	MPI	7	25	20	20	34	30	36	31	11	15
Number of citations to articles published in last 4 years <sup>b</sup>	Cambridge	–	80	100	150	130	180	80	40	110	100
	Jodrell Bank	–	40	40	30	30	20	10	20	40	20
	NFRA	–	90	80	70	50	100	160	130	70	130
	MPI	–	50	100	80	90	140	80	120	80	110
Citations per paper for publications of last 4 years	Cambridge	–	2.0	1.9	3.2	3.0	3.9	2.9	1.5	2.5	3.0 <sup>c</sup>
	Jodrell Bank	–	2.6	2.3	1.8	2.3	2.3	0.9 <sup>a</sup>	3.2 <sup>a</sup>	2.3	2.1
	NFRA	–	3.8	2.9	3.1	2.0	2.1	2.8	2.5	2.9	2.5
	MPI	–	1.5	2.1	1.9	1.7	2.2	1.2	1.9	1.8	1.8

<sup>a</sup> These figures are based on an analysis of less than 10 papers and may therefore not be statistically very significant.

<sup>b</sup> All the citation figures have been rounded to the nearest 10.

<sup>c</sup> This is “weighted” average derived by adding up the citation totals for each year, and dividing by the sum of the publication totals.

Table 7  
Highly cited papers on theoretical radio astronomy

		1969–78		1979–83	
		No. of papers	No. of times papers were highly cited	No. of papers	No. of times papers were highly cited
Cited 12 or more times in a year	Cambridge	10	29	2	5
	Jodrell Bank	1	2	0	0
	NFRA	5	13	5	8
	MPI	5	16	1	1
Cited 15 or more times in a year	Cambridge	6	12	1	4
	Jodrell Bank	0	0	0	0
	NFRA	2	8	3	3
	MPI	3	9	0	0
Cited 20 or more times in a year	Cambridge	4	6	1	4
	Jodrell Bank	0	0	0	0
	NFRA	1	1	1	1
	MPI	1	4	0	0

Besides the obvious decline in output and impact of Cambridge theoretical work, it can be seen that the contribution of Jodrell Bank has also not reached the level attained in the previous ten-year

period – comparatively few theoretical papers have been published by observatory staff since 1978 and they appear to have had little overall impact, earning an average of only 20 citations a year (see

Table 8  
Relative positions of the four observatories in terms of their contributions to theoretical astronomy, 1969–78 and 1979–83

		Cambridge	Jodrell Bank	NFRA	MPI
1969–78	Annual average publication rate <sup>a</sup>	1.5	4	3	1.5
	Average number of citations to work of last 4 years <sup>a</sup>	1	4	2.5 <sup>c</sup>	2.5 <sup>c</sup>
	Average citations per paper <sup>a</sup>	2.5 <sup>c</sup>	2.5 <sup>c</sup>	1	4
	Numbers of highly cited papers <sup>b</sup>	1	4	3	2
	“Average” position for above 4 indicators <sup>c</sup>	1.5	3.6	2.4	2.5 <sup>c</sup>
1979–83	Annual average publication rate <sup>d</sup>	3	4	2	1
	Average number of citations to work of last 4 years <sup>d</sup>	2.5 <sup>c</sup>	4	1	2.5 <sup>c</sup>
	Average citations per paper <sup>d</sup>	1	3	2	4
	Number of highly cited papers <sup>b</sup>	2	4	1	3
	“Average” position for above 4 indicators <sup>c</sup>	2.1	3.8	1.5	2.6

<sup>a</sup> Based on the figures in the penultimate column of table 6.

<sup>b</sup> Based on the figures in table 7.

<sup>c</sup> See footnote 6.

<sup>d</sup> Based on the figures in the last column of table 6.

<sup>e</sup> Denotes equal second position (after allowing for the limits of reliability that can be attached to the data reported here).

table 6 above). The most significant improvement has come in the case of NFRA which doubled both its average annual output of theoretical papers (from 6 to 13 per annum) and the impact made on the scientific community (with total citations rising from 70 to 130 a year).

## 5. Discussion and conclusions

Although the approach employed in the bibliometric analysis here represents an improvement over that used in the original study, and the resulting figures are in many instances different, the overall picture that emerges of the comparative contributions to observational radio astronomy over the period 1969–78 is, as we have seen, broadly similar. Consequently, it would appear that the technical flaws, which undoubtedly existed in the “prototype” methodology used in the first study, did not significantly influence the findings, and, most importantly, did not result in unjustified conclusions being drawn about the relative research performance of the four observatories. This said, a number of points can be made by way of summary.

(1) As in the earlier study, the various indicators of contributions to observational radio astronomy suggest that Cambridge was overall the most successful of the four observatories in the period 1969–78, and was probably the world-leader in this field, although it was closely followed by NFRA. Both seem to have made considerably greater observational contributions than MPI and Jodrell Bank (see table 4, above). Cambridge was in addition apparently the most successful in terms of its theoretical work in the ten years up to 1978, earning more citations on average and producing a larger number of highly cited papers. However, since 1979 there has been a considerable decline in its relative standing for both observational contributions (by the end of 1983, it had probably fallen to fourth position behind Jodrell Bank) and theoretical work. We cannot comment in detail on the reasons for this decline since we have not undertaken the necessary interviews with radio astronomers at Cambridge and other observatories. Nevertheless, it is significant that Sir Martin Ryle, the source and inspiration of many technical and scientific in-

novations during the previous 25 years, gradually transferred his research interests to other fields, in particular the study of alternative energy sources, for the last few years before his death in 1984. Furthermore, some of the observatory’s other prominent members have moved on to posts elsewhere. Also of importance has been the absence of a major new capital facility, with the main telescope (the 5-kilometre interferometer commissioned in 1972) gradually becoming overshadowed by newer facilities around the world. Whether the fortunes of observational astronomers at Cambridge will be restored in coming years as they start to exploit the new telescope on Mauna Kea, the “enhanced” 5-kilometre telescope, and perhaps also the innovative attempt to carry out aperture synthesis at optical wavelengths remains to be seen.

(2) In the case of Jodrell Bank, the main conclusion is, as before, that its telescopes contributed rather less to observational radio astronomy over the period 1969–78 than those operated by Cambridge and NFRA, although the gap between it and these two leading observatories was smaller than suggested in the original study. It was also apparently not as successful as the others in terms of its contributions to theoretical astronomy. Furthermore, a comparison of tables 4 and 5 suggests that the investment in new telescope facilities during the second half of the 1970s did not apparently greatly improve its relative standing between 1979 and the end of 1983 although the situation may have altered since then.

(3) Likewise, there has been little change since 1979 in the comparative performance of NFRA as regards contributions to observational radio astronomy made by users of the telescopes it operates – for both periods considered, it has been one of the leading observatories. According to the indicators shown in table 8, however, there has been an improvement in its contributions to theoretical astronomy, with NFRA researchers probably achieving greater overall success in this area than their three sets of rivals over the period 1979–83.

(4) The biggest improvement in terms of relative contributions to observational radio astronomy seems to have been made by the Max-Planck-Institute for Radio Astronomy (see tables 4 and 5). MPI researchers have, according to the figures in table 8, also slightly improved their

comparative standing in terms of theoretical astronomy.

Given the controversy surrounding the publication of the results from our original study, we shall refrain from attempting to draw explicit policy conclusions. Instead, we shall conclude by sounding two notes of caution in relation to the results of research evaluations such as that reported here. First, the findings need careful interpretation: in particular, it is important to understand the factors that have structured research performance in the past. Such factors then need to be carefully analyzed to evaluate the extent to which they are likely to exert an influence in the future.<sup>19</sup> In the case of the Mullard Radio Astronomy Observatory at Cambridge, for example, to what extent was the success up to the end of the 1970s due to the influence of a few key individuals, or to the development of innovative telescope technology (in particular, aperture synthesis), or more widely to being part of a particularly stimulating research environment (the Cavendish laboratory)? What have been the reasons for the apparent decline since then, and what, if anything, could be done to reverse it?

Second, the results of research evaluations do not in themselves offer a solution to the perennial problems of science policy, not even to those specific to the difficult decisions on increasing or decreasing funding for a large central facility or laboratory. Suspicion among scientists about the dangers of policy-makers seizing upon such information to take effective control over such decisions away from the research community itself undoubtedly contributed to the initial hostility to bibliometric and other external assessments of scientific performance. Consequently, we should stress, as we have on several previous occasions, that the results of such assessments are likely to be most effectively used when they are fed into the mechanism traditionally employed in science policy-making, namely peer-review. In this way, a wide constituency of scientists (and not just those in the field concerned) will be provided with the systematic information needed to take an effective part in the decision-making process, at the very least enabling them to ask more informed questions about the performance of large research

facilities competing for increasingly scarce resources. Since the earliest attempts to apply quantitative techniques to research evaluation, the range of bibliometric indicators available has grown, as has confidence in their relevance to science policy issues and in their reliability. That the necessary resources have been invested in the difficult and often contentious process of developing research evaluation techniques is due in large part to farsighted science policy officials like Yvan Fabian, to whose memory this issue of *Research Policy* is dedicated.

### **Methodological appendix – Identification of highly cited papers**

One of the main defects of the methodology employed in the original radio astronomy study concerns the procedure used for identifying highly cited papers. Rather than compiling figures on the numbers of citations earned by papers in every year after publication, it was decided, after testing a sample of papers, to adopt a simplified procedure. Initially, citations were recorded for each paper just in even-year editions of the *Science Citation Index (SCI)* – either the first and third year after publication, or the second and fourth year, depending on whether the paper was published in an odd or even year. Only in cases where a paper received six or more citations in an even year were the citations in odd years scanned. It was assumed that such a procedure would succeed in identifying nearly all highly cited papers (at least to the level of accuracy required for evaluation purposes) on the grounds that citation rates of the papers examined did not seemingly fluctuate by more than a factor of two or so from one year to the next. While this procedure was successful in identifying nearly all papers cited 15 or more times in a year, it “missed” several of the papers cited between 12 and 14 times in a year on just one occasion.

In the present study, therefore, a more rigorous procedure was adopted. For *every* paper, the number of citations was compiled in the year of publication and in each of the next three years. For papers earning five or more citations in the third and subsequent years, the citations were also recorded, this process continuing until the number fell to four or less in one year. While this proce-

<sup>19</sup> A provisional, first attempt to show how this might be undertaken is described in Martin and Irvine [21].

ture is a significant improvement over that used previously, it will still fail to pick up papers that only became highly cited after four or more years. However, experience in another field (high-energy physics), where citations were recorded for each paper for the first *ten* years after publication, leads us to expect the number of such papers to be very small. From the point of view of compiling a definitive historical account, this “short-cut” might still be deemed unacceptable, but in applied policy research, where the costs of assessment need to be kept to a small fraction of those for the research activities being evaluated, a sensible balance has to be struck between expense and comprehensiveness.

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