Recent years have seen great interest in exploring universal gravitation both by astronomical and geophysical observations and by experiments in terrestrial laboratories. This book is about laboratory experiments, the reasons for doing them and the difficulties they present.

Gravitation is a very weak force and experiments will be useful only if they are at the limits of sensitivity and mechanical measurements. They must be imaginatively designed and carefully performed. They are especially afflicted by noise and other disturbances, the effects of which the authors analyse in detail, as they do issues in the design of experiments. Critical accounts are given of experiments for testing the inverse square law and the principle of equivalence and for measuring the constant of gravitation.

The book will be of value to graduate students, research workers and teachers engaged in any precise measurements or in theoretical or experimental studies of gravitation, who wish to understand the problems of laboratory experiments in this and similarly demanding fields.

GRAVITATIONAL EXPERIMENTS IN THE LABORATORY

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Preface

From the time that Newton first proposed that there was a universal force of gravity inversely proportional to the square of the distance between two point masses, there have been recurrent investigations of how far that rule was correct, and many different alternative forms have been suggested. The other assumption that Newton made, that the force of gravity did not depend on the chemical composition of bodies, has also been questioned from time to time; Newton himself carried out the first experimental test of what has become known as the weak principle of equivalence. It has often been suggested that some apparently anomalous behaviour in celestial mechanics should be ascribed to a failure of the inverse square law; indeed Clairaut developed the first analytical theory of the motion of the Moon because of discrepancies between Newton's theory and observation that might have been due to an inverse-cube component of the force. As with all subsequent studies before general relativity, careful analysis showed that the effects were consistent with the inverse square law. General relativity predicts a small deviation from the inverse square law close to very massive bodies, a deviation that has been confirmed by careful observation.

The motions of celestial bodies about each other are, with very minor exceptions, unable to reveal any departure from the weak principle of equivalence; if such departures are to be detected, they must be sought in laboratory experiments or geophysical observations. It has been argued that geophysical observations show failures of the simple Newtonian law of gravitation, but the most recent studies have not confirmed earlier results and are wholly consistent with the inverse square law and the weak principle of equivalence. Experiments in the laboratory, that is to say, at distances of no more than a few metres, have been performed to check the inverse square law at short distances and to examine the weak principle of equivalence, and again the outcome is that no deviations have been found from either. We may say that, at the present time, no departure from the predictions of general relativity has been confirmed and that general relativity remains the best theory of gravitation that we have.

None the less the nature of gravitation remains an enigma. Is it simply a matter of the geometry of space-time, or is it related to deeper physical symmetries as are the other principal forces of nature? The force is extremely weak and seems independent of any other physical circumstance, so that experimental investigations are very difficult, and up to now they have, as has just been said, confirmed the inverse square law and weak equivalence. Experiments on gravitation in the laboratory are therefore a great challenge to technique and imagination in design and performance, and many able experimenters have accepted that challenge over the last four decades, partly to examine the predictions of theories other than general relativity, partly to follow up indications from geophysical studies that there might have been failures of general relativity. As in geophysical studies, general relativity holds the field.

The considerable effort that has been spent on laboratory investigations should not be thought nugatory. The effects looked for are very small and push experimental design, technique and analysis to the limits. Consequently the general art of precise measurement has been greatly advanced by the search for anomalous effects, as well as by attempts to improve the precision of the measurement of the constant of gravitation, a constant that is still only poorly known. We have therefore thought it useful to describe the principal experiments that have been done in recent years, placing them in the historical context of earlier work and indicating possible future developments. We draw particular attention to the limitations set by noise and extraneous disturbances, for those are common to all very precise measurements and not just to experiments on gravitation. Experimental physicists in general, and not only those interested in gravitation, will, we trust, find value in our accounts of the very precise experiments that have been done and in the emphasis that we place on the importance of imaginative design carefully thought through. Theorists also, we hope, may find it useful to have a general critical account of the experimental evidence relevant to their investigations.

It seems that many programmes of laboratory investigations of gravitation are drawing to a close and that new ideas for experiments are needed if there is to be any prospect of detecting deviations from general relativity. The only realistic hope for radically different experiments may well lie in doing them in spacecraft, but while various experiments have been proposed, none has yet been accepted into a flight programme. Now therefore seems a suitable time to bring together the methods and results of recent work, giving, as they have, a generally negative answer to the question whether deviations from general relativity can be detected in laboratory experiments, but also having generated important advances in experimental technique.

There are many publications about the study of gravitation. We have been greatly helped by the publication of two bibliographies, one for the constant of gravitation (Gillies, 1987) and the other (Fischbach *et al.*, 1992) for work relevant to a possible 'fifth force'.

We have been much indebted in our studies of gravitation over the years to many colleagues in Cambridge and North America and mention, in particular, Dr P. L. Bender, Professor Sir Brian Pippard, Dr J. Faller, Dr G. Gillies, Dr A. J. F. Metherell, Dr Riley Newman, Dr C. Speake and Dr T. J. Quinn. One of us (A. H. C.) owes an especial debt to the late Professor Antonio Marussi, a friend and colleague over many years, whose untimely death was a great loss to geophysics and the study of gravitation. We take great pleasure in thanking those who have looked after us at Cambridge University Press, notably our editor, Dr S. Capelin, and our copy-editor, Sheila Champney.