The need for synoptic optical solar observations from the ground

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Summary

The Sun can impact society through long-term and short-term changes. We cannot understand or potentially predict such variations unless changes in the solar state are monitored with the best possible suite of measuring systems. A variety of approaches including space- and ground-based instruments are currently engaged in this task and we focus here on the ground-based optical wavelength systems. There are many advantages of ground-based observations, including reliability, longevity, cross-calibration, cost, flexibility and educational outreach. Funding agencies need to recognize the value of long-term observations and provide sufficient resources to obtain and improve the measurements. The most important augmentations are to support new instrument scientists and their involvement with ground-based long-term solar observations and to develop a facility for archiving and dissemination of solar observational results similar to the Heliospherics Events Knowledgebase.

Introduction and Goals

The purpose of this white paper is to describe the scientific motivation for long-term ground-based solar observations, discuss the many advantages of these types of systems, provide the status of existing US facilities, and discuss what is needed to keep these systems in the forefront of heliophysics.

Note that the scope of this white paper is limited to synoptic ground-based optical observations. Long-term space-based observations, such as total solar irradiance (TSI) measurements, ground-based radio observations (i.e. FASR) and high-resolution ground-based solar observations (i.e. ATST) will be covered in other white papers.

Scientific Motivation

The generation of cosmic magnetic fields is one of the great mysteries in physics. How is it that macroscopic magnetic fields can be created and continually maintained in galaxies, planets, and stars on time scales of billions of years? In the case of the Sun, this question has been asked in the context of the dynamo mechanism of the solar activity cycle during which the number of sunspots is seen to rise and fall over a period of 9 to 13 years while the polarity of the global solar magnetic field reverses with a roughly 22-year period. During times of maximum sunspot population, the activity of the sun in terms of the occurrence of flares and coronal mass ejections (CMEs) is also at a maximum. These events can affect daily life in modern human society, as they are able to disrupt the technology that has become a vital part of our daily lives. Telecommunications, air transport, space activities, navigation, and power grids have all been adversely affected by events on the Sun and there are mechanisms whereby solar activity may be able to influence climate.

Thus, understanding the basis of solar activity is both a major scientific goal and an important societal activity. Since the activity cycle takes place on decadal time scales, its understanding requires long-term observations on the order of hundreds of years. Indeed, the study of solar activity can be dated back to 364 BC when the Chinese astronomer Gan De recorded sunspots in a star catalog. This was followed by about 2000 years of sporadic naked-eye sunspot observations in China, the Middle East and Europe, culminating with the 1610 invention of the telescope and Galileo's subsequent realization that sunspots were not planetary transits. After this, sunspot observations became more regular and accurate, to the point that, in 1843, Schwabe was able to detect a cyclical change in the number of sunspots. This led Wolf to examine the historical record of observations in the 17th and 18th centuries, and to devise the sunspot number which is still used to characterize the level of solar activity today.

While synoptic observations of the Sun are frequently used in short-term projects, their true value is in long-term datasets - some tendencies may only become apparent from the perspective of long-term variations. How many of us have thought in the past: "if I only had the data from the previous cycle to verify my theory"? Synoptic observations are the data providers for future studies.

For example, more than 100 years of observations of the Sun in Ca K spectral line taken by several observatories are still being used in studies of long-term variations in solar irradiance. The synoptic solar full disk longitudinal magnetic maps taken at Kitt Peak, the Wilcox Solar Observatory, and Mt. Wilson are the only data sets covering multiple activity cycles for studying the role of polar magnetic fields in setting the cycle characteristics and the open magnetic field affecting the TSI. These studies were not conceived of at the beginning of synoptic observations, but with the advances in understanding of solar phenomena, the data are available to all researchers investigating these questions.

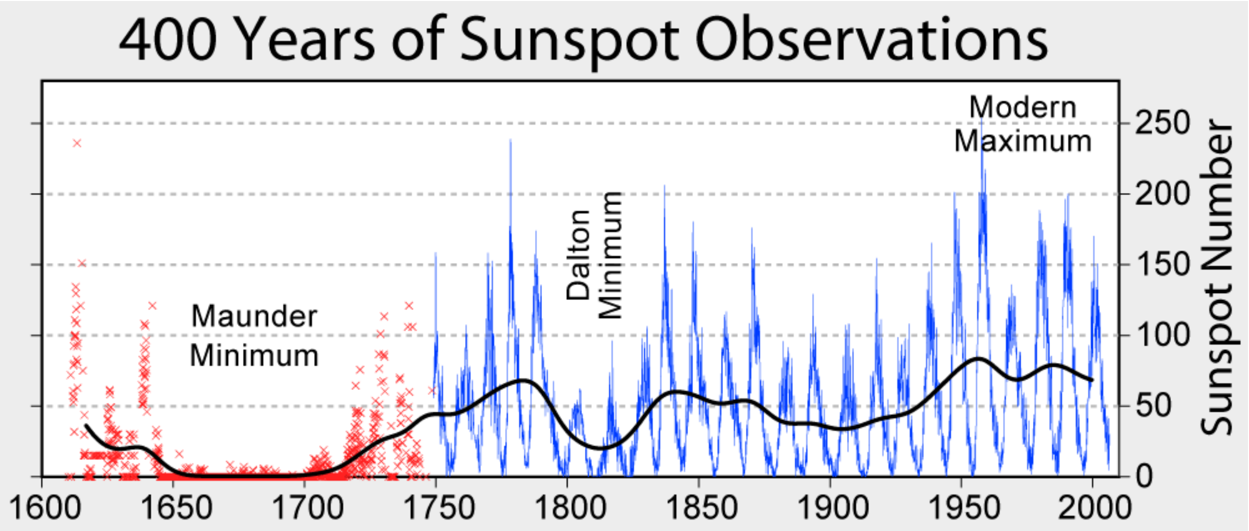

Figure 1: The sunspot number as a function of time over the last 400 years. The blue curve shows the monthly averages recorded by the Royal Observatory of Belgium. The red points are earlier, less reliable observations. The black curve shows the long-term variations. This figure was prepared by Robert A. Rohde and is part of the Global Warming Art project.

Figure 1 shows the number of sunspots as a function of time over the last 400 years. An uncertainty in this reconstruction comes from the need to adjust records from different observers to a common scale – a problem that continues to be present in a different but related form today. Figure 1 clearly shows the long-term variability of the level of solar activity. In particular, it shows the Maunder minimum when very few sunspots were visible. This period was also the time of the "Little Ice Age" in Europe, suggesting that there may be a link between solar activity and terrestrial climate. The large variability in amplitude of the sunspot number, along with the 40% range of the length of the cycle, suggests that the currently limited number of observed cycles (23 as of now, with cycle 24 just beginning) is insufficient to fully characterize the underlying dynamo mechanism and that we must continue to obtain observations over many more cycles.

This need is also indicated by the recent deep and peculiar solar minimum between cycle 23, which ended in 2008, and cycle 24, which only began with a significant number of spots in late 2009. During this minimum, which was 1.5 years longer than most, the Sun reached a very deep quiescent state with

- The most spotless days since cycle 15
- The lowest global solar wind pressure of the space age
- A solar magnetic field 36% weaker than last minimum

- Probably the lowest irradiance yet measured
- The lowest sustained 10.7-cm radio flux since 1947
- An unusually high tilt of dipole field
- No classical quiescent equatorial streamer belt
- Very high cosmic ray flux

Except for the first item in this list, none of these other aspects of the deep minimum were observable before WWII since the technology was not yet developed. In addition, there are considerable problems with using the sunspot number as an indicator of solar activity. Variations in observer bias, equipment, and terrestrial atmospheric conditions over 250 years make it extremely difficult to reliably compare important details of the activity. For example, there is now evidence that the strength of the magnetic field in sunspots has been declining over the last 20 years, and that the associated decrease in contrast will render sunspots invisible in the next 15 years or so. It is very possible that the same process occurred during the Maunder minimum, particularly since the Carbon 14 record indicates that the cosmic ray flux was being modulated with solar cycle periods during that time even though no sunspots were visible.

In addition to the space-age era measurements that date back three to five cycles, there are even newer measurements that are essential to unravel the solar cycle. One of these new techniques provides vector magnetic field observations to provide the direction of the surface magnetic field as well as an estimate of the true magnetic field strength and filling factor. Routine and consistent observations of the vector nature of the solar magnetic field are in their infancy, with sporadic ground-based observations dating back to the 1968 and synoptic programs starting up in the first decade of the 21st century. These observations have already detected a previously unknown and highly variable horizontal component of the solar magnetic field. The solar cycle dependence of the vector nature of the magnetic field is unknown at this point. We now know that the TSI is related to the distribution of magnetic field on the solar surface, but the relationship between TSI and the direction of the magnetic field has not yet been studied.

We now also have measurements of the velocity field inside and on the surface of the Sun. Velocity field measurements on the surface date back to the 1980s, and helioseismology has provided continual measurements of the flows inside the sun since 1995. These new internal flow measurements, particularly of the north-south meridional and the east-west zonal flows, are already being used by dynamo theorists to constrain their models.

A future measurement that is just now becoming possible is the direct measurement of the magnetic field in the solar corona. These observations will be invaluable for understanding the structure and dynamics of the corona over the solar cycle. Studies of this type are currently limited to using intensity images as proxies for the magnetic field. Interpreting this type of data has many challenges due to thermal and projection effects. Knowledge of the coronal magnetic field dynamics is also essential for studies of flare activity and CME evolution.

It is thus essential that long-term modern solar observations continue indefinitely in order to understand the solar cycle and the related activity that affects modern society. In the next section, we will discuss the advantages of using ground-based optical systems for this research.

Highlights of Science Results from Ground-Based Observations

A large number of fundamental solar characteristics have been discovered from ground-based measurements. Historically, some of the most significant are:

- Discovery of sunspots
- Discovery and measurement of solar surface differential rotation (the first astrophysical measurement)
- Discovery of the solar cycle
- Discovery of flares
- Discovery of the solar magnetic field
- Discovery of solar convection: granulation and supergranulation
- Discovery of the solar five-minute oscillations, development of helioseismology
- Discovery of the corona
- Discovery of the chromosphere
- Determination of the internal rotation rate

Some more recent discoveries and accomplishments are:

- Discovery of the horizontal magnetic field
- Discovery of flare-associated magnetic field changes
- Relationship between east-west zonal flows (torsional oscillation) and cycle timing
- Relationship between north-south meridional flows and cycle timing and amplitude
- Discovery of a secular decrease in sunspot magnetic field strength
- Relationship between subsurface vorticity and flares
- Discovery of coronal oscillations
- First measurements of coronal magnetic fields

Why ground-based?

In this era of significant solar scientific results from space-based solar missions such as SOHO, TRACE, Hinode, STEREO, SDO, etc. one might wonder why ground-based observations are needed. There are, in fact, several advantages of ground-based systems for long-term solar observations.

Only ground-based systems can reliably provide consistent long-term observations since instruments on the ground are always accessible and can be repaired. One can recall a loss of SOHO for an extended period of a few months. At that time, ground-based observations from NSO's Kitt Peak Vacuum Telescope were the only source of full disk solar magnetograms. Solar space missions are much less accessible, especially in the orbits to which they are now being launched (e.g. SOHO, STEREO, SDO). Satellites in near-earth orbit are accessible, but the transportation costs to the site are several orders of magnitude higher than for ground-based locations. Space missions are vulnerable to radiation exposure and micrometeorite collisions, and have limited lifetimes due to agency support and hydrazine consumption. In addition, space weather affects satellites reducing their utility as sources of space weather data at critical times.

Ground-based systems can be operated with much simpler and less expensive logistics than space missions. This is particularly true in terms of the return of the data from the instruments. Solar data rates are typically quite high, and are constantly increasing with advances in detectors and computing technology. Space missions have telemetry limits which restrict the amount of data return, and which require costly ground antennas to receive. Ground-based systems are limited only by disk-drive and tape capacities, which can be easily and inexpensively increased.

Ground-based observations are necessary to establish continuity between different space missions. An example is provided by the transition from SOHO/MDI to SDO/HMI. The calibration for MDI magnetograms was updated several times during the SOHO mission based on ground-based Mt. Wilson observatory measurements. A recent working group meeting has indicated that the new HMI vector magnetic field data may have unknown instrumental polarization that could be characterized using comparisons with ground-based observations. The cross-calibration of long-term observations over several decades is needed to provide a robust basis for understanding the Sun. In addition, synoptic ground-based solar irradiance measurements on a sustained basis with a cross-calibrated set of instruments provide a reliable reference for space measurements.

Table 1: US Ground-Based Solar Observatories

Observatory	Facilities	Data provided	Location	Founded
Big Bear Solar Observatory	New Solar Telescope	Magnetic fields, helioseismology, photometry	California, Global Hα network HQ	1969
High Altitude Observatory/NCAR	Mauna Loa Solar Observatory, 2 coronagraphs, 2 chromopheric imagers, photometer	Coronal magnetometry & photometry, chromospheric imaging, photospheric photometry, helioseismology	Colorado (HQ), Hawaii (MLSO)	1940 (HQ) 1979 (MLSO)
Mees Solar Observatory	Polarimeter, spectrograph, coronagraph	Coronal magnetic fields and photometry, vector magnetic fields, photometry	Hawaii	1964
Mt. Wilson	150-ft and 60-ft Towers	Helioseismology, surface velocity fields, magnetic fields	California	1904
National Solar Observatory	Dunn ST, McMath-Pierce ST, Evans facility, GONG, SOLIS	Vector & LOS magnetic fields, helioseismology, photometry	New Mexico, Arizona, GONG network HQ	1947 (NM) 1959 (AZ)
San Fernando Observatory	Five telescopes, spectroheliograph, IR camera	Photometry	California	1976
Wilcox Solar Observatory	Magnetograph	Global magnetic fields	California	1975

Ground-based observations allow us to preserve and extend consistent data sequences. One of the big hindrances regarding any transition towards operational space weather products is that one needs large statistical databases on which to train, or develop a particular system, and then the same system needs to be available in order to provide the data for subsequent predictions. Long-term data provide essentially our only option for "control" data sets. As a remote observing science, our choices are limited in this really fundamental aspect of being able to perform physics experiments.

Ground-based observatories have great flexibility in testing innovative techniques and developing new capabilities. For example, chromospheric magnetic field measurements will provide a significant enhancement to photospheric magnetograms. It is likely that first routine full vector chromospheric magnetogram capability will be developed at a ground-based observatory, before a future space mission. Ground-based observations typically employ state-of the art instrumentation using the most modern technology that does not have to withstand the rigors of the space environment. This often leads to important discoveries that subsequently guide the design of space-based instruments.

Ground-based observatories provide valuable opportunities for students to acquire hands-on experience in developing and operating instrumentation. This is very important for training and educating future generations of solar physicists and instrumentalists for both ground- and space-based programs.

Finally, ground-based observations impose many fewer restrictions on international collaboration as compared with space-based instrumentation. Limitations on advanced knowledge and technology transfer can restrict international collaborations in space research, while cooperation in ground-based observations can widen the collaboration and effectively share the costs of acquiring synoptic data.

Current Status

There are a number of ground-based observatories that are providing long-term optical solar measurements. In the US, these are listed in Table 1.

One of the most productive developments of ground-based solar observing systems has been the introduction of global networks, which are sets of instruments distributed geographically around the world. Networks are able to observe the sun nearly continuously for many years with only brief losses of data due to weather and equipment issues. Networks provide consistent observations spanning many years and are useful for capturing brief transient events. There are currently three major networks in operation: BiSON (Birmingham Solar Oscillations Network, non-imaging helioseismology, began operations in 1979), GONG (Global Oscillation Network Group, imaging helioseismology, began operations in 1995); and the Global High-Resolution Hα Network (Hα images, began operations in 2000). This observing strategy has proven to be very effective for general solar physics, as shown by the addition of magnetic field measurements and Hα images to GONG. One of the major goals of the next decade is to develop and install a network of instruments for vector magnetic field measurements.

There are several more ground-based solar observatories outside the US. Table 2 lists ones that are partners in global networks.

Table 2: Non-US observatories that are part of a global network

Observatory	Network	Location
BISON	Birmingham Solar Oscillation Network	United Kingdom (HQ)
Catania	Global Hα	Italy
Cerro Tololo	GONG	Chile
Hairou	Global Hα	China
Instituto Astrofisica de Canarias: La Palma and Teide Observatories	GONG	Spain
Kanzelhöhe	Global Hα	Austria
Learmonth	GONG	Australia
Meudon	Global Hα	France
Pic-du-Midi	Global Hα	France
Udaipur	GONG	India
Yunnan	Global Hα	China

Plans

All of the observatories listed in Table 1 have upgrades either in progress or planned. Typical projects range from improvements to data processing /storage facilities and new detectors to new instruments and even new telescopes. These projects range in cost from $10k to $300M. These projects will not be discussed in this white paper since the small ones are typically funded out of the observatories' operating budgets and the large ones will each have an associated white paper. These larger projects include a vector magnetic field network, an upgraded imaging helioseismology network, the Mauna Loa Solar Observatory coronagraph, the HAO COronal Solar Magnetism Observatory (COSMO), and the Advanced Technology Solar Telescope (ATST).

Needs

It is clear that long-term consistent observations are vital tools for understanding the Sun and its activity that impacts modern society. However, there seems to frequently be a preference in funding agencies for building new facilities, rather than the long-term operation of older systems. While the agencies certainly have many pressures from the research community and from Congress, the agencies should recognize the value of long-term continual consistent observations to understand the solar cycle and to provide relevant space weather data. We estimate that the current combined annual cost of running all of the observatories in Table 1 to be about $25-30M.

In addition to new instruments, it is important to maintain older instruments. The objective of establishing a reliable long-term record means that some instruments need to remain as nearly constant as possible. Many observable quantities depend on the details of how the solar spectrum is sampled so that changes in the record of the solar state may be from changes in the instruments rather than from changes in the Sun.

There are a number of specific areas where improvements could be made to increase the already substantial contribution of the ground-based observatories to heliophysics:

- Provision by the funding agencies to provide 3% annual budget increases to cover inflation.
- Quasi-periodic allocations for capital improvements in the form of instrumentation and detector upgrades and other improvements that reduce operations costs while enhancing scientific return on the investment in facilities.
- Establishment or augmentation of an associated theory program at each observatory to provide closer interaction between theory and observations.
- Establishment of a line of funding for research in statistical analysis specifically targeting space weather forecasting.
- Establishment of a national program to encourage and financially support new instrument scientists.
- Initiatives to establish new faculty positions in solar and space physics in order to increase student training in research and broaden the national research effort in this highly relevant area.
- Increased funding for the archiving, distribution, and analysis of ground-based data.
- Targeted funding for educational outreach programs at all levels combined with programs to broaden the participation of underrepresented groups.

With these improvements, the national investment in existing solar observatories would provide additional benefits to society in terms of increasing our ability to understand and forecast solar activity.