

## TWENTY-FIVE YEARS OF HELIOSEISMOLOGY RESEARCH IN UZBEKISTAN

**Sh. A. Ehgamberdiev**

*Ulugh Beg Astronomical Institute, Uzbekistan Academy of Sciences,  
Astronomicheskaya 33, Tashkent 700052, Uzbekistan.*

Email: shuhrat@astrin.uz

**E. Fossat**

*Observatoire de la Côte d'Azur, CS 34229, 06304 Nice Cedex 4, France.*

and

**A.V. Serebryanskiy**

*Ulugh Beg Astronomical Institute, Uzbekistan Academy of Sciences,  
Astronomicheskaya 33, Tashkent 700052, Uzbekistan.*

---

**Abstract:** The Ulugh Beg Astronomical Institute was involved in the IRIS helioseismology project from the mid-1980s through to the end of the project in 2001. This project aimed to study the deep interior of the Sun using Doppler spectral line shift measurements integrated over the whole solar disk. In order to obtain long, continuous observational data showing periodicity a network of six stations more or less regularly distributed around the globe and equipped with identical spectrophotometers was deployed. One of these instruments was installed on Mt Kumbel in Uzbekistan in 1988. In addition, from 1996 to 2002 the Ulugh Beg Astronomical Institute was involved in observations for the TON project, which was aimed at carrying out helioseismic studies of the subsurface structure of the Sun and its dynamics.

The participation of the Ulugh Beg Astronomical Institute in both projects was crucial not only for obtaining long-term observational data, but also for the scientific analyses of the observational data and the preparation of the resulting research papers. Many scientific results came out of these two projects, but more importantly, many graduate students used these projects to obtain their Ph.D.s.

**Keywords:** helioseismology, Uzbekistan, Ulugh Beg Astronomical Institute, IRIS, TON, Kumbel Observatory

---

### 1 INTRODUCTION

After the discovery of the solar five-minute oscillations in the early 1960s (Leighton et al., 1962), it took about a decade before there was a clear understanding that this surface phenomenon was merely the visible part of the seismic waves that emanated from the interior of the Sun (Ulrich, 1970). In the early 1970s helioseismology began to develop as an efficient method of probing the interior structure and dynamics of the Sun.

In fact, these seismic waves are, physically speaking, acoustic waves that are excited by the turbulent noise of the boiling nature of the solar surface. The frequencies of these waves are not, of course, in the range of those of our usual music, but the comparison of the helioseismic methods with listening to music is quite relevant. The solar frequencies are about 100,000 times slower than the typical musical frequencies. As there are nearly 100,000 seconds in one day, this comparison explains why a few hundred seconds of 'musical listening' require a few hundred days of continuous measurement of the solar oscillations. Then, the scientific benefit for solar physics is similar to the 'musical benefit' of carefully listening to music (the music itself, instruments, their perfect or imperfect tuning, interpretations, etc.). But instead of a knowledge

of musical culture, helioseismologists just need some physical and mathematical skills. Then they can access the distribution of certain physical parameters (density, temperature, chemical composition, local motions such as rotation or convection, etc.) throughout the spherical volume of the Sun.

The acoustic noise at the solar surface excites the resonance of many eigenfrequencies. These resonances are trapped in a volume defined by acoustic reflection near the surface (acoustic waves cannot move out) and an internal acoustic refraction that eventually forces the waves that are moving downwards to return towards the solar surface. These eigenmodes can be as different as the global resonance of the total volume of the sphere on the one hand, and the resonance of just a thin layer under the surface of the photosphere on the other hand. But some of them can also be very similar, with a small frequency difference that is mainly due to a small difference in the depth of the resonant volume. In this case, their frequency difference becomes a nearly direct measurement of the value of the sound speed at their deepest penetration, so that a 'nearly direct' measurement of the sound speed from the solar surface to the solar core can be determined if many of these frequencies can indeed be obtained from obser-

ations. Mathematically speaking, it means an inversion of the differential measurements.

Fortunately, nearly 10 million resonant modes of oscillation are observable at the solar surface. The response of the solar surface to the superposition of all seismic waves resembles motions at the surface of an ocean. The detection of these modes is a really challenging task, since the velocity amplitude of a typical acoustic mode (p-mode) is of the order of 1 cm/sec, with an associated intensity variation of about  $10^{-7}$ . Such minute oscillations can be detected by measuring either the Doppler shifts of a spectral line or the intensity of the optical radiation.

The main task of observational helioseismology is the determination of the individual p-mode frequencies and their other parameters. The measurements must be made continuously over a long period of time in order to determine oscillation frequencies with the extremely high precision necessary to make useful inferences about the solar interior. As we have seen, these useful inferences are coming from the small differences of neighboring resonant modes. These observational time series should be as uninterrupted as possible because gaps in the data produce spurious peaks (sidelobes) in the oscillation power spectrum, which hinder subsequent analyses.

The first attempt to obtain uninterrupted observations was made by a University of Nice team at the Geographical South Pole during the southern summer of 1979/1980 (Grec et al., 1980; 1983). As a result of six days of nearly continuous observations it was possible for the first time to resolve individual peaks in the solar oscillation power spectrum. For this pioneering work Eric Fossat, Gerard Grec and Martin Pomerantz were awarded a Gold Medal by the Royal Academy of Belgium. Shortly afterwards it was realized that the atmospheric conditions at the South Pole would not allow continuous observations for longer than about one week. However, in order to resolve the multiple structure of an individual peak, uninterrupted observations for as long as a few months were required.

This fact explains why all observing programs developed in the 1980s aimed at obtaining continuous observations over periods of months, and even years, in order also to track the variations that occurred in all helioseismic parameters in the course of the solar cycle. Three main ideas were considered in order to obtain continuous observations for longer than the typical 8-12 hour daily run possible at any mid-latitude single site. The first was to go to the Antarctic, where—as previously mentioned—during summer uninterrupted observations were possible for as long as one week. Another option was to detect solar oscillations from space, where a suit-

able instrument located on a spacecraft with a totally sunlit orbit could provide uninterrupted observations over a period as long as the lifetime of the spacecraft. The third idea was to deploy a network of observing sites around the globe, that were suitably located at complementary longitudes and latitudes.

In 1982 IAU Commission 12 voted for the following resolution: "... recognizing the extreme importance of the observation of solar seismology ... [and] strongly supporting international co-operation in establishing a worldwide network of observing stations." The team from the Laboratoire d'Astrophysique at the University of Nice presented a project named IRIS (International Research on the Interior of the Sun) to the French astronomical agency (INSU) in 1983 and it was funded from 1984. Thus the IRIS network project was launched, along with the GONG project in the USA (Harvey et al., 1996). As the core instrument of the IRIS project, a sodium cell spectrophotometer providing full-disk Doppler shift measurements of the sodium D1 line was suggested (Grec et al., 1991). The plan was to install these instruments at six complementary sites around the globe.

The first IRIS network spectrophotometer was installed in 1988, on a remote mountaintop site at Kumbel in Uzbekistan (Figure 1). Further IRIS stations were then deployed at the rate of one per year until 1994 when the sixth spectrophotometer was installed at Culgoora, Australia. Meanwhile, the first data were acquired in July 1989 (when Kumbel was the only network station), but were immediately complemented by a summer campaign using a prototype magneto-optical filter instrument that was designed by A. Cacciani and operated at the Jet Propulsion Laboratory in California (Cacciani and Fofi, 1978). Thus, the first day of IRIS data acquisition already marked the beginning of a two-site network program.

The headquarters of the IRIS project were established at the University of Nice in France, and Figure 2 shows the worldwide geographical distribution of IRIS stations.

Here it is necessary to mention that observations made with the IRIS instrument were spatially unresolved, combining light from the entire visible surface of the Sun (i.e. observing the Sun as a star), which limited the detectability to only those modes of oscillation whose wavelengths were comparable to the diameter of the Sun and hence could penetrate down to the solar core. P-modes registered with spatial resolution provided information on the sub-surface structure of the Sun (see paragraphs on the TON project in Section 4 below). Figure 3 shows examples of low degree p-modes (top row) and high degree p-modes (bottom row) accessible by imaged helioseismology.



Figure 1: A panoramic view of the Kumbel IRIS station established in Uzbekistan in 1988 (photograph: Sh. Ergamberdiev).

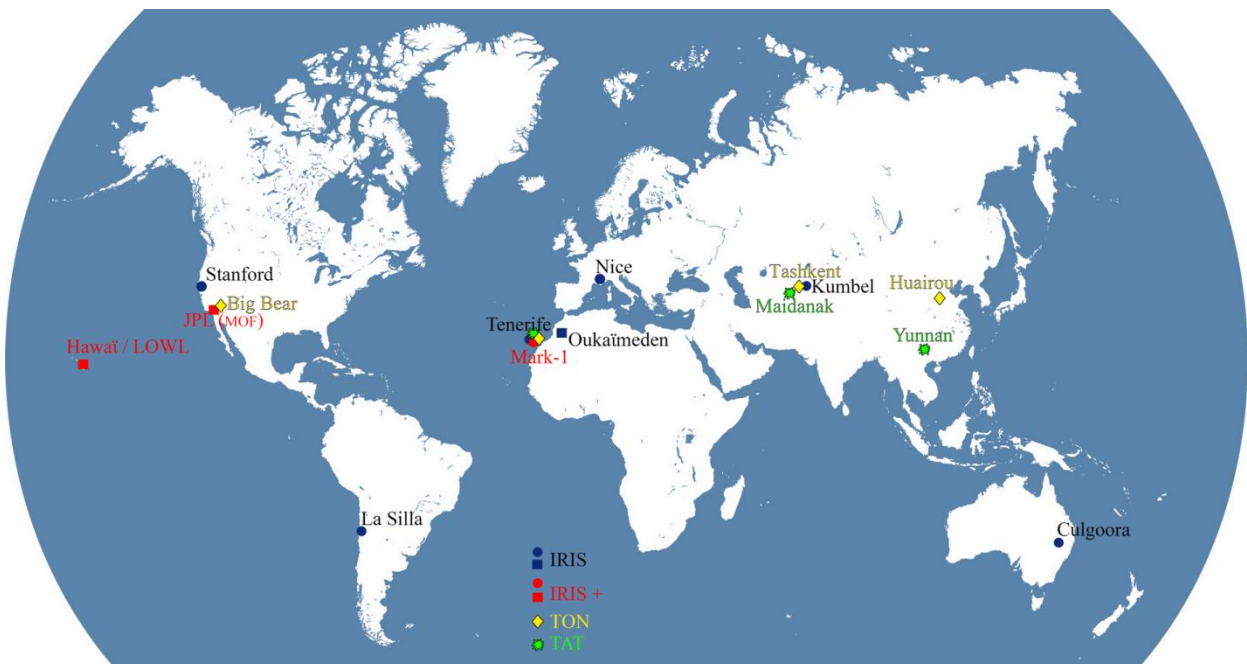


Figure 2: The worldwide IRIS and TON networks. Those shown by red squares are stations of the other full-disk helioseismology projects whose data were merged with the IRIS data. See the text for details. The stations of the TAT (Taiwan Automated Telescope) asteroseismological project are also shown.

Reviews of the first eleven years of the IRIS project were presented in Fossat et al. (2002) and Fossat (2013). This present paper mainly focuses on the participation of the Uzbekistan team in the IRIS project (which ended in 2001).

## 2 THE IRIS STATION AT KUMBEL MOUNTAIN

Within the distribution of the northern hemisphere sites selected for the worldwide IRIS network, one instrument had to be installed some-

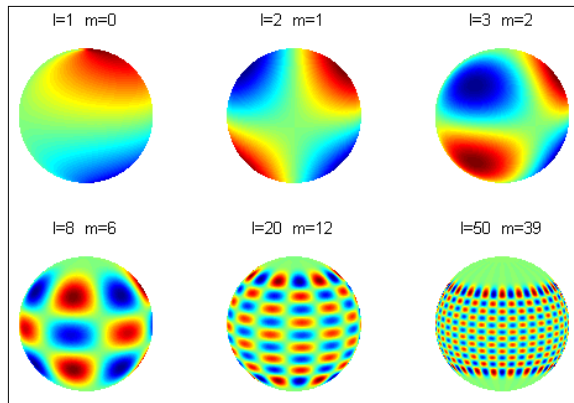


Figure 3: Examples of low degree p-modes (top row) and high degree p-modes (bottom row) accessed by imaging helioseismology.

where in Central Asia. On the basis of an analysis of meteorological data and after visual inspection of several pre-selected sites, it was finally decided to install an instrument on top of Kumbel mountain, 75 km northeast of downtown Tashkent and at an altitude of 2300 m above mean sea level (Bajumanov et al., 1991a; 1991b).

Since Kumbel was an isolated remote mountain, in contrast to other intended stations in the network, it was necessary to build not only a shelter for the spectrophotometer but also living facilities for observers. All this construction work was done during the summer of 1988 and 'first light' at Kumbel was recorded in August 1988. A personalised story of this fantastic astronomical adventure is recounted in Appendix I. Figure 1 shows the Kumbel station and Figure 4 the IRIS instrument that was installed at this station.

During its eleven years of operation (one full solar cycle) the Kumbel station alone provided the IRIS data bank with more than 40% of the total observational data. However the contribution of the Kumbel team to the success of the IRIS project was not limited to only providing data as the Uzbek astronomers also actively participated in all subsequent stages of the work, such as data analyses and the writing up of the resulting research papers.



Figure 4: A close-up showing the spectrophotometer at the Kumbel IRIS station (photograph: Sh. Ergamberdiev).

Here we have to mention that before scientific analyses of the observational data began, there was a long process of selection, characterization and calibration in m/s of the velocity signal due to the solar oscillations. The first version of a software package which took into account Doppler shifts caused by all known astronomical motions contributing to the line-of-sight velocity between the instrument and the solar surface was developed in Tashkent (Ehgamberdiev et al., 1991a). It also took into account the apparent residual velocity generated by the non-uniform integration of the solar rotation in the Earth's stratified atmosphere (Ehgamberdiev and Khamitov, 1991). During the Second IRIS workshop, Shuhrat Ehgamberdiev was elected Chairman of the raw data calibration software team, and other members were Eric Fossat (Nice), Bernard Gelly (Nice), Shukur Kholikov (Tashkent), Pere Palle (Tenerife) and Luis Sanchez (Tenerife). The main duty of the team was to produce a complete software package which would select and calibrate the data, in order to obtain for each day and each site a velocity-versus-time signal. Data obtained at each IRIS station had to be subjected to this procedure before it was possible to merge them into a resulting single data string.

Figure 5 illustrates two daily data records obtained at the Kumbel and Oukaïmeden stations on 27 July 1989 after applying the calibration subroutine. The high coincidence of the records (see, for example, the small-scale variations around 9.8 h UT) obtained at these two sites, which were separated by about five hours in longitude, demonstrates first of all the high sensitivity of the IRIS spectrophotometer to detect such tiny solar oscillations, and secondly the efficiency of the calibration software.

Figure 6 shows an average of about 100 daily solar oscillation power spectra and the level of so-called solar noise (solid line) caused by motions in the solar atmosphere (granulation, supergranulation, etc.) estimated by J. Harvey (1985). This power spectrum appears to be photon noise-limited in the high frequency range and solar noise-limited at low frequencies. For a long time the low frequency noise level estimated by J. Harvey was regarded as not being accessible by ground-based observations. Figure 5 first of all shows that the level of that noise should be recalculated as it was over-estimated. On the other hand it demonstrates the ability of the IRIS instrumentation and data analysis to detect solar oscillations.

### 3 SCIENTIFIC RESULTS

#### 3.1 Single Site Data Analysis

Usually an 'IRIS day' began at Kumbel where observations were started around 1h UT. During

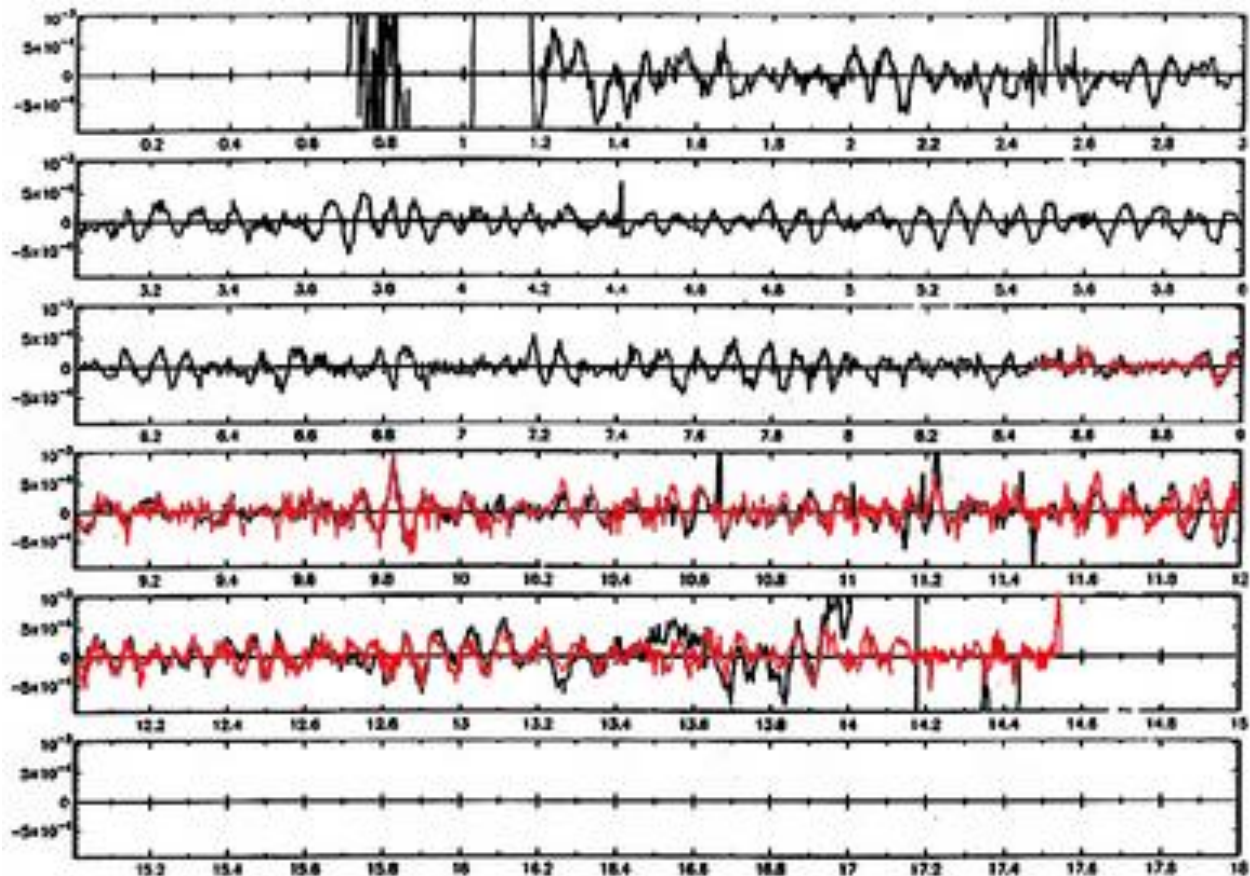


Figure 5: Two merged records showing 7.5 hours of solar oscillations obtained on 27 July 1989 at the Kumbel (black line) and Oukaïmeden (red line) stations.

the first two years of operation of the Kumbel spectrophotometer, which began in July 1989, many high-quality daily data were collected. However, it was not possible to compile a long-duration data-set because at that time the IRIS network was not yet completely deployed (in particular, La Silla and Stanford were not fully operational). Another reason was the absence at that time of an appropriate data-merging procedure, which was only developed later (see Fossat, 1992). In such a situation, our curiosity to learn something about the physics of the p-modes could only be satisfied through the analysis of data from a single site.

At a single site, one day of observations typically lasted 10-11 hours and thus provided a daily power spectrum with a frequency resolution  $\sim 25\text{-}30 \mu\text{Hz}$ . This was not enough to resolve individual peaks, but it was enough to show the discrete nature of the power spectra. Peaks in the daily power spectra implied four or six unresolved individual p-modes.

Despite a less-than-optimistic view of this approach adopted by some theorists, two important scientific results were extracted from the low-resolution daily power spectra.

For the study of the statistical properties of p-modes, 99 days of data obtained solely at the Kumbel station were used. Comparisons of the

different daily power spectra showed that the peaks had quite high amplitude fluctuations with time. However, by itself this was not an indication of a temporal amplitude modulation of p-modes. Upon making certain assumptions about the partial amplitude interdependence and individual p-mode phase independence, the amplitude modulation rate was estimated to be about 25% (Ehgamberdiev et al., 1992). This result appeared to be inconsistent with the more-or-less generally-accepted theory of the interaction between the oscillations and stochastic turbulent

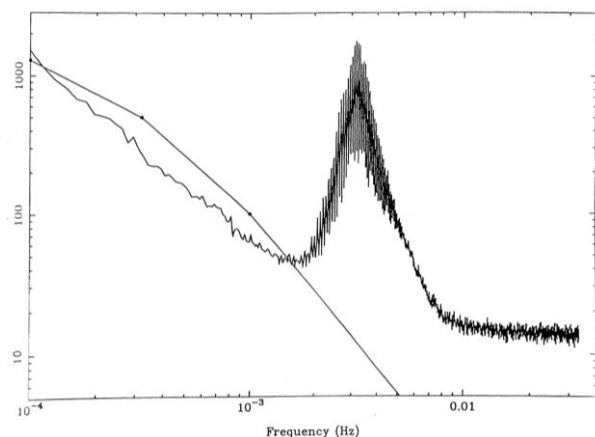


Figure 6: The average of about one hundred daily solar oscillation power spectra and the level of noise (solid line) caused by motions in the solar atmosphere (supergranulation etc.) (after: Ehgamberdiev et al., 1990: 21).

convection. Meanwhile, theories on the physical mechanism invoked for the p-mode excitation had to satisfy this new constraint, and explain the p-mode energies, their frequency range and line-widths. Theorists from Liege University in Belgium carried out research on the interpretation of this interesting observational result (see Gabriel and Lazrek, 1994).

Another result obtained through an analysis of data from a single site related to the measurement of the acoustic cut-off frequency. Solar acoustic p-modes exist because acoustic waves can be trapped inside cavities in the interior of the Sun, where they are reflected back and forth between lower and upper boundaries of the cavity. Near the solar surface, the reflection occurs due to rapid changes in density and sound speed. Reflection takes place only for waves with frequencies less than a critical one, commonly called the 'acoustic cut-off frequency'. Acoustic waves with frequencies higher than this cut-off frequency can propagate through the solar atmosphere.

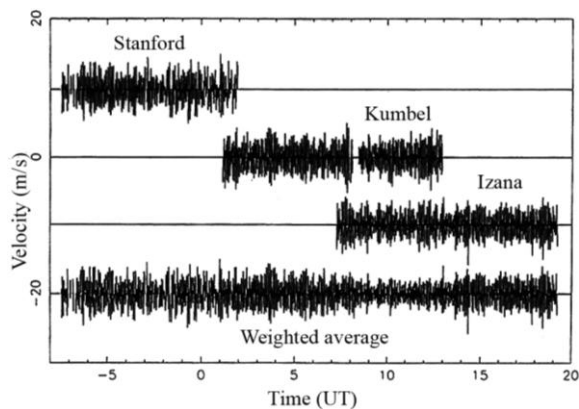


Figure 7: An example of a very successful day when three stations provided 100 percent coverage of data, along with their weighted average.

The average power spectrum of observations made at the IRIS stations of Kumbel, Izana, La Silla and Oukaïmeden was used for this analysis. The value of  $5.55 \pm 0.1$  mHz was obtained for the acoustic cut-off frequency using these observational data, but this appeared to be higher than any of the theoretical predictions. A surprisingly-precise measurement of the acoustic cut-off frequency of the solar atmosphere proved that helioseismology was not necessarily limited to the deep interior.

Using data from the IRIS network obtained between 1989 and 1996 (inclusive) we attempted to see if there were any changes in the values of the acoustic cut-off frequency of the solar low- $l$  p-modes in the course of the solar cycle. Upon applying three different methods of analysis we found that the cut-off frequency was variable, changing from  $5.77 \pm 0.02$  mHz at sunspot maximum to  $5.37 \pm 0.04$  at sunspot minimum (Serebryanskiy et al., 1998).

The good quality of the IRIS data at high frequencies above this cut-off made it possible to provide solar physicists with an answer to an old question about the heating of the chromosphere. The acoustic power density that exists between the cut-off frequency and the frequency after which it becomes flat (photon noise) can be used to estimate the acoustic energy flux that dissipates in the chromosphere. The estimated value of that energy ( $\sim 10^7$  erg/cm<sup>2</sup>/s) appeared to be just enough to compensate for the energy losses in the chromosphere (Athay, 1970).

### 3.2 The Sun as an Instrument that Produces 'Repetitive Music'

In an ideal case all helioseismology projects aim at obtaining the best temporal coverage of data as close as possible to 24 hours a day and 365 days a year. This is mainly in order to avoid the presence of 'sidelobes' in the Fourier spectra. These sidelobes, or artificial secondary peaks, interfere with other peaks that are real, and thus make accurate p-mode parameter measurements difficult. However, the ultimate goal of 100 percent duty cycle (percentage of filling with data) is hardly ever achieved by any of the observing programs, so the analyst is always faced with the presence of gaps in the time series subjected to Fourier analysis.

Figure 7 shows a successful day when three stations provide 100 percent coverage data, and their weighted average. However, such a situation was not often achieved. In fact, the network duty cycle reached better than 60% only in the northern summers, but was down to much less than 50% during the winters due to bias in the geographical locations of the IRIS stations (four in the northern hemisphere and just two in the southern hemisphere), and also due to the large longitude gap represented by the Pacific Ocean.

Facing this situation, it was decided to develop cooperation between the IRIS team and scientific groups operating other helioseismology instruments. Data from several summer seasons of the JPL's Magneto-Optical Filter project (Cacciani et al., 1988), the Mark-1 potassium data from the Tenerife site of the BiSON network (Elsworth et al., 1988) and the integrated signal from the LOWL images obtained at Mauna Loa in Hawaii (Tomczyk et al., 1995) were merged with the IRIS signal to produce a time series we called IRIS<sup>++</sup>. As a result, the duty cycle of the IRIS data was strikingly improved, but it was capable of further improvement. After testing different deconvolution algorithms, an interesting method of partial gap-filling was developed. It should be noted here that the standard mathematical deconvolution technique completely ignored the specific properties of the signal. However, taking into account what we knew about

the signal itself helped us to approach the problem from another perspective and try to predict with a high level of confidence the signal which was not observed (Fossat et al., 1999).

To take advantage of what we knew about solar oscillations at the time, we turned our attention to the IRIS autocorrelation function. We filtered the signal in the p-mode frequency range from 1.5 to 5 mHz and saw that after about four hours the signal had a very high level of coherence (>70%). Just like musical songs, this suggested that the solar oscillations were almost periodic, i.e. repetitive in time, with a quasi-periodicity of a little more than four hours (Fossat et al., 1999). This fact is demonstrated in Figure 8, where a solar oscillation signal is cut into three parts, each 4.1 hours apart, and these are shown one below the other. The marked similarity of the signals does not require any additional comment.

With this specific feature of the solar oscillation it became obvious that simply replacing a gap by the signal collected four hours earlier or four hours later provided a gap-filling method with a confidence level of >70%.

This idea was extremely simple. Doing it in practice also was very simple, and it was demonstrated that p-mode helioseismology was not so demanding of the duty cycle. In the most extremely-favorable situation, we could imagine a data set with just a 33% duty cycle, containing four hours of data followed by an eight hour gap, and so on. After this 'repetitive music' gap-filling, it was hardly possible to distinguish a Fourier peak from the original one.

Surprisingly, what started as a pure mathematical problem finally acquired a physical meaning. We realized that what we were seeing in the autocorrelation was evidence of the returning acoustic waves after they had travelled all the way down to the other side of the Sun through the center, and back to the visible surface! This took about one hour along any one radius, and thus four hours for the complete return trip.

### 3.3 Frequency Determination from IRIS Network and IRIS<sup>++</sup> Data

The seismic exploitation of helioseismological data requires extremely accurate measurements of the acoustic mode frequencies. With a line-width  $\sim 1$   $\mu$ Hz, a large number of p-mode frequencies can be estimated with an uncertainty of half their line-widths, i.e. about  $10^{-4}$  in relative terms. Although such accuracy looks impressive, it appears insufficient when facing the demand of theoretical seismic inversions, which require relative accuracies of about  $10^{-5}$  in order to improve the existing solar models. At such a high level of demand, the task becomes harder.

A first attempt at p-mode frequency estimation from the IRIS data obtained during four summer seasons (1989-1992) was made by Gelly et al. (1997). Beside IRIS data, the analysis included the magneto-optical filter measurements of Cacciani et al. (1988) and the data of the BiSON network's potassium instrument in Tenerife (Elsworth et al., 1988). Even with these additional data sets, the duty cycle did not exceed 50%.

The next attempt to estimate the precise frequencies was made by Serebryanskiy et al. (2001) using 7.5 years of IRIS data, from 1989 to the end of 1996. This work included not only the p-mode frequencies, but also their variation during the solar cycle, their line-widths and their profile asymmetries. However, the relatively low duty cycle (still less than 50%) again limited the accuracy of the results.

After exploiting the 'repetitive music' gap-filling method, an extended list of IRIS p-mode frequencies and rotational splitting was published by Fossat et al (2002). In that same year a list of frequencies and splitting from nearly 2,000 days of GOLF data was published by Gelly et al (2002). Two lists of GOLF frequencies, from low

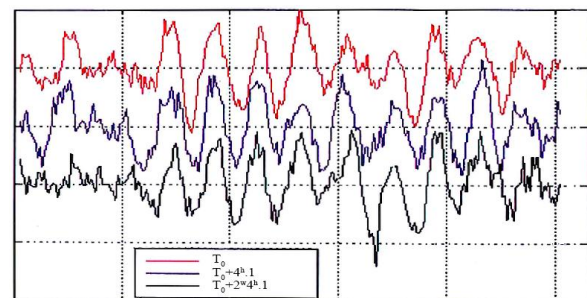


Figure 8: The solar oscillation signal cut in three parts 4,1 hours apart and shown one under another. The horizontal time span displayed here is one hour.

activity and high activity, could be averaged and compared to the IRIS frequencies averaged over the complete solar cycle. The mean difference across the entire frequency range was almost zero (just a few nHz).

This precise low degree p-modes frequency determination and the subsequent modeling of the internal structure of the core was an important contribution to the resolution of one of the most important task of solar physics: the solar neutrino puzzle.

The Sun is a natural nuclear fusion reactor. A proton-proton chain reaction converts four protons into helium nuclei, neutrinos, positrons and energy. The excess energy is released as gamma rays, as kinetic energy of the particles and as neutrinos—which travel from the Sun's core to the Earth without any appreciable absorption by the Sun's outer layers. The measurement of the solar neutrino flux is extremely difficult since neutrinos essentially do not inter-

act with anything, but the derived values were between one third and one half of the values that were predicted by modelling the solar interior. This discrepancy, which lasted from the mid-1960s to about 2002, came to be known as the ‘solar neutrino problem’.

Early attempts to explain this discrepancy proposed that the temperature and pressure in the interior of the Sun could be substantially different from what was computed using solar models. However, these solutions became more and more untenable as advances in helioseismology made it possible to measure the interior temperatures of the Sun right through to the solar center, with an incredibly high precision of better than  $10^{-3}$ . Helioseismology and the ‘cold’ solar core definitely proved to be inconsistent.

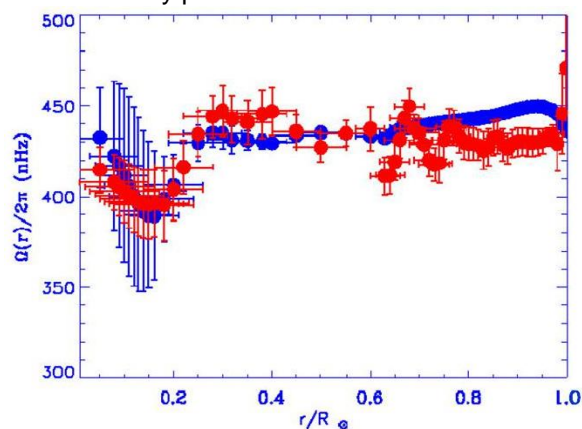


Figure 9: This plot shows the equatorial profile of the solar rotation using p-modes frequency splitting measurements from IRIS and MDI data on board the SOHO spacecraft. Comparison of profiles obtained using low and intermediate modes (blue) and a one obtained using only low-degree (red) modes ( $l=1-4$ ) shows that the rotation profile along the whole solar radius can be obtained with only the low degree p-modes (after: P.M. Di Mauro, pers. comm., 2002).

The discrepancy has since been resolved by new understanding of the physics of neutrinos. Essentially, as neutrinos have mass, they can oscillate and change from one type to another. However, the detector developed by Raymond Davis Jr. was sensitive to only one type, so instead of detecting all solar neutrinos it only one recorded a fraction of them, between one third and one half.

For their pioneering work on the resolution of the solar neutrino problem Davis and Masatoshi Koshiba shared the 2002 Nobel Prize in Physics.

### 3.4 Solar Core Rotation

The Sun does not rotate as a solid body. The latitudinal differential rotation, easily visible at its surface, has been demonstrated by helioseismology to persist down to the base of the convection zone, at a depth of  $0.71R_{\odot}$ . The rotation of the solar core could be much faster, if the loss of angular momentum by the solar wind during the 4.5 billion-year life of the Sun on the Main Sequence had not been efficiently coupled

to the very deep and dense layers. The rotation of the upper internal layers down to the base of the convection zone had been determined with amazing precision by imaging helioseismology (Libbrecht, 1988). The deeper layers of the Sun remained inaccessible until the two main ground-based networks for full disk (i.e. unresolved) helioseismology, IRIS and BiSON, were able to accumulate enough observations to provide access to the measurement of the low degree p-modes splitting influenced by the rotation of the solar core. From 1993, the IRIS group attempted to measure this value (Loudagh et al., 1993; Fossat et al., 1995), and in 1996 they published the result of their most reliable analyses based on three time series, each a little longer than four months, obtained during the northern summers of 1990, 1991 and 1992 (Lazrek et al., 1996). The unexpectedly low value of the rotational splitting implied a solar core rotation rate that was no faster than the envelope, and possibly was even slower. This result was confirmed by the BiSON group (Elsworth et al., 1995), and later by the 11-year IRIS data bank, as well as by the comparison between IRIS and GOLF measurements (Fossat et al, 2002), that helped to reduce the error bar by one more step.

Figure 9 shows the solar core rotation obtained by Di Mauro et al. (1998) using our IRIS splitting values together with MDI data. It is extremely interesting to note that most of the rotation along the total solar radius can be obtained with only the low degree ( $l=1-4$ ) p-modes. This opens up exciting perspectives for asteroseismology!

Measurements of the rotation of the solar core are related to the classical question about the interpretation of Mercury's orbital precession. This problem was first addressed in the 1800s. Due to various effects, such as tiny perturbations caused by other planets, the observed precession of Mercury's orbit is about 532 arc-seconds per century. A significant part of this value was explained in terms of Newtonian gravitational theory, but the residual 43 arcsec per century that could not be explained in this way was the subject of long discussion until Einstein (1915) demonstrated that his General Theory of Relativity predicted precisely that amount.

If the solar core would rotate about ten times faster than its envelope (as all stellar evolution theories predict), then the Sun should have the shape of a flattened spheroid. In this case it cannot be assumed that its gravitational field would exactly suit the inverse square law. As soon as the Sun is not an ideal spherical body, then Einstein's theory can explain only a fraction of the residual effect. The IRIS measurements proved that the solar core does not rotate faster



than its envelope (i.e. it has a period of about one month). Due to this unprecedented result, obtained through the IRIS project, deviations in the Sun's gravitation field from the inverse square law can be ignored.

### 3.5 Variation of Helioseismic Parameters During the Solar Cycle

The long duration of the observations obtained through the IRIS project allowed an analysis of variations in the solar p-mode frequencies and other parameters in the course of the solar cycle. Such analyses played a crucial role in our understanding of the physics behind the variations that occur during the solar cycle as manifested, for example, by changes in sunspots and the switching of the magnetic poles about every eleven years. The mode frequency turned out to be the most sensitive parameter.

Analyses of IRIS++ frequencies of low-degree solar p-modes confirmed the overall trend of the p-mode frequencies from the minimum to the maximum of solar activity. The frequencies remained almost unchanged below 2 mHz, then in the range 2.0–3.7 mHz the frequencies increased with increasing solar activity. Above 3.7 mHz, the frequency shift dropped to zero, and became negative for frequencies higher than 4.5 mHz (Salabert et al., 2004; see Figure 10). It also was interesting to investigate shorter periodicities in the frequency shift and the detailed correlation of the shift with various solar cycle indices such as the sunspot number and the 10.7cm radio flux. Upon analyzing separately the even and odd degree modes it was found that even modes reacted later than the odd modes, which seemed more closely correlated with solar activity short-time fluctuations. This was interpreted as a consequence of the geometry of the modes.

The mode amplitude and line-width also showed a dependence on solar activity. It was found that the mode amplitude anti-correlated with the solar cycle while the line-widths correlated with changing solar activity. It also was found that the overall change in the amplitudes was approximately  $-26\%$ , and for the line-width was typically  $+11\%$ . Regarding the velocity power, this was anti-correlated with solar activity, showing a variation of about  $-11\%$ , but a correlation was found between the solar activity cycle and the energy supply rate.

The resulting line-width obtained with IRIS++ data seemed to confirm what Houdek et al. (2001) had suggested, namely that the damping rate for the modes in the range of 2.4–3.0 mHz increased when the horizontal size of solar granules decreased from solar minimum to solar maximum (Muller, 1988) but their vertical size remained constant. Using these two parameters the velocity power of the modes as well as the

energy supplied to them were estimated and it was found that the velocity power changed by  $-11\%$ , while the rate of energy supply remained constant with solar activity.

### 3.6 Mode Profile Asymmetry

Another interesting problem we addressed within the IRIS project was the mode profile asymmetry observed in power spectra of solar p-modes. It was found that p-mode profiles were not pure Lorentzian, but displayed an excess of power at lower or higher frequencies in part depending on the observational techniques used to analyze the solar oscillations. It was realized that asymmetry resulted from a combination of two effects: localization of the source of the p-mode oscillation and the visibility of the source itself (the so-called 'correlated noise'). To extract the asymmetry parameters from the IRIS

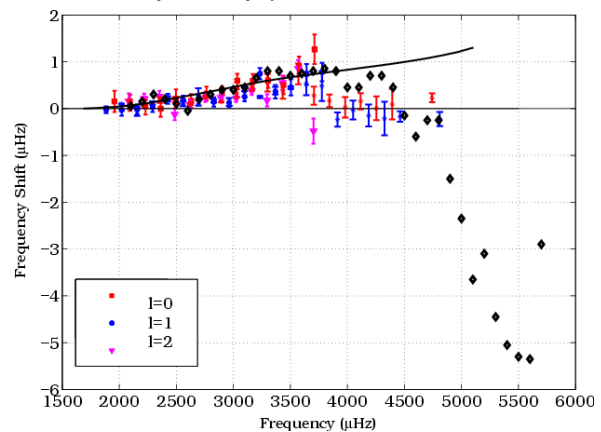


Figure 10: The IRIS frequency shifts in the frequency range from 1.8 mHz to the acoustic cut-off frequency. Using different methods it was possible to confirm the overall trends of the p-mode frequencies from solar minimum to solar maximum. However, the values and signs of these trends are different for different modes (after Salabert et al., 2004: 1138). See the text for details.

power spectra we fitted the p-mode profiles using the formalism of Nigam and Kosovichev (1998). Our results qualitatively agreed with the results of the BiSON project (Chaplin et al., 1999), and more details can be found in Serebryanskiy et al., 2001.

## 4 THE TAIWAN OSCILLATION NETWORK PROJECT

The Taiwan Oscillation Network (or TON) is a ground-based network set up to measure ionized calcium K-line intensity oscillations in order to study the internal structure of the Sun (Chou et al., 1995). The TON project was funded by the Taiwanese National Research Council from the summer of 1991, with the headquarters located in the Physics Department at the National Tsing Hua University (NTHU) in Hsinchu, Taiwan, where the telescope systems were designed, built and tested. The first TON network telescope was installed at the Teide Observatory,

Tenerife, Canary Islands (Spain) in August 1993. The second one was installed at the Huairou Solar Observing Station near Beijing in January 1994, and the third telescope system was installed at the Big Bear Solar Observatory, California, in June 1994. The locations of these and other TON stations are shown in Figure 1.

The TON was designed to obtain information on high-degree solar p-mode oscillations, along with intermediate-degree modes. The TON network used 3.5-inch Maksutov-type telescopes to observe K-line full-disk solar images with 16-bit  $1080 \times 1080$  water-cooled CCDs. The diameter of the Sun was set at 1000 pixels. The measured amplitude of intensity oscillations was about 2.5%. The TON instruments provided data on the solar p-modes with a spherical harmonic degree,  $l$ , as high as 1000.

#### 4.1 Local Helioseismology at the UBAI: An Historical Retrospective

Initially Uzbekistan was not going to be part of the TON collaboration, but Shuhrat Ehgamberdiev persuaded Dean-Yi Chou that Uzbekistan could play a significant role, so in 1996 a TON instrument was installed in Tashkent on UBAI land (Figure 11). It is necessary to mention here that, unlike the IRIS instrument, the TON experiment was not sensitive to the atmospheric transparency gradient, and required good seeing for high-resolution imaging. It was well known that the atmosphere in Tashkent was very calm in the hottest season, with maximum clear day-time. To avoid the influence of ground turbulence which aggravated image quality the TON instrument was placed on top of a 6-m high pillar. As a result, it was easy to achieve a resolution of 2 arc-seconds and access modes with  $l$  up to 1000.

Following the deployment of the TON telescope in Tashkent the UBAI was the most active member of the TON team. As in the case of building the IRIS station, all work on the installation of the TON instrumentation was done by Taiwanese and Uzbek teams, without involving any professional builders. The Tashkent instrument provided the TON network with daily observations from 1996 until 2002. Besides carrying out observations, the UBAI team also actively participated in the scientific analyses. In 1998 Shukur Kholikov, who at the time was a senior researcher at UBAI, was invited to NTHU to work with the local helioseismology team using TON data. His work foreshadowed the success that would occur in the next few years after Alexander Serebryanskiy and later Oleg Ladenkov joined NTHU to continue research on local helioseismology using TON and SOHO/MDI data (Scherrer et al., 1995). Their efforts resulted in a series of papers on new methods and results in

helioseismology, including the study of the lifetime of the high-degree solar acoustic modes, meridional circulations and a search for evidence of magnetic fields at the base of the solar convection zone.

#### 4.2 The Main Scientific Results Obtained Through the TON Project

The most important scientific result obtained using helioseismology and TON experimental data was the first estimation of sunspot depth. The story of this discovery is very interesting.

After the successful installation of a TON instrument in Tashkent Dean-Yi Chou went to Hawaii to attend a meeting on helioseismology. There he met Barry Labonte who told him about an interesting method of submarine detection, announced in *Nature* (Buckingham et al., 1992). Two different well-known methods of submarine detection used 'active' and 'passive' techniques. The active method consisted of illuminating an underwater object with a pulse of sound, and its presence was inferred from the echo it produced. The passive approach involved simply listening for the sound that the object itself emitted. The method suggested by Buckingham relied on using the scattering of acoustic noise by an object. The ocean is filled with incoherent noise which has many natural sources. An object drowned in such an ambient acoustic field modifies this field by scattering acoustic energy in all directions. This scattered radiation can be focused into an image using some kind of acoustic lens (say an acoustic reflector or refractor). After appropriate signal processing, an image of the object can be displayed on the computer monitor.

This breakthrough idea was used by Dean-Yi Chou and co-workers in a helioseismological study of changing acoustic noise background by a sunspot. The method was called acoustic imaging (Chang et al., 1997; Chen et al., 1998; Chou et al., 1999; Chou, 2000), since it allowed a check to be made layer by layer of the presence of a sunspot at different depths. Figure 12 demonstrates how contrast of a sunspot, which absorbs the acoustic energy, changes with depth. One can see that traces of the sunspot are disappearing at a depth of about 40,000 km. For the first time scientists were able to peer through the solar atmosphere down to deep inside the solar interior in order to investigate the formation of active regions.

From our everyday experience we knew that an image of the object illuminated by scattered daylight could be formed by an optical lens. The solar acoustic waves, which were continuously generated and dissipated stochastically by turbulent convection, played the same role as ambient light. However, unlike an experiment in the



Figure 11: View of the TON instrument installed in Tashkent in 1996 (left) and its platform (photograph: Sh. Ehgamberdiev).

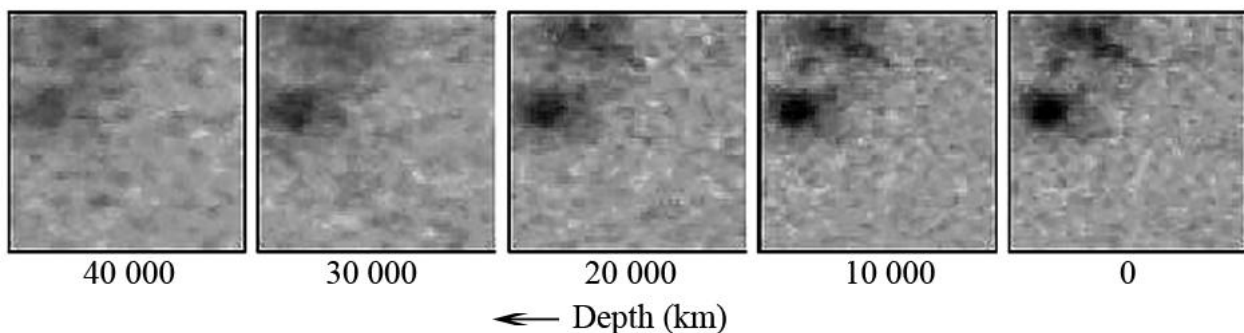


Figure 12: This shows a direct acoustic image at the surface of the Sun (far right) and acoustic images reconstructed at various depths for the active area NOAA 7993. One can see that the suppression of acoustic intensity increases with depth. At 40,000 km below the surface the signature of the sunspot almost disappears (after Chang et al., 1997: 826).

ocean, in the case of the Sun it was impossible to use a parabolic reflecting dish. For ambient acoustic imaging of the Sun ‘a computational acoustic lens’ was used. It had to be taken into account that different p-modes had different paths and arrived at the surface at different times and at different distances from the target points. On the basis of the relationship between travel time and the distance traveled by the acoustic waves, the intensity of the acoustic signal at the target point was coherently detected.

A similar method was developed by Lindsey and Braun (1997) but this was a solely mathematical approach, while the work of the TON team included the mathematical method and the application of the method to observational data. Especially, they proposed to use time-distance curves, which were the key to the method to be realized.

#### 4.2.1 Life-time of the High-degree Solar p-modes

The excitation and damping mechanism for acoustic solar oscillations (p-modes) is conventionally analyzed by measuring p-mode profiles in power spectra of solar acoustic oscillations. The lifetimes of the high- $l$  solar p-modes are difficult to measure with the conventional method due to

the broad width of these mode profiles in power spectra and mode blending. The TON team was the first to use the time-distance technique to measure the lifetime of the wave packets formed by the high- $l$  p-modes (Burtseva et al., 2007; Burtseva et al., 2009; Chou et al., 2001; Chou and Ladenkov, 2007). This method allowed the measurement of the lifetime of the central mode of the wave packet as a function of frequency.

#### 4.2.2 Meridional Circulation in the Solar Convection Zone

Instead of the old ‘pot-on-the-stove’ model of vertical convection of the Sun, horizontal jet streams were found in the top layer of the convective zone. Small ones were found around each pole, and larger ones that extended to the equator were called ‘meridional circulation’ or ‘meridional flows’.

Meridional circulation in the solar convection zone plays a crucial role in flux transport dynamo theories. For example, the time-scale of the solar activity cycle depends on the structure and magnitude of the meridional circulation.

Using the TON data obtained between 1994 and 2003 the TON team found that an additional divergent meridional flow component existed and its change with time correlated with the

magnetic fields of the 11-year cycle. This divergent flow extended down to  $0.8 R_{\odot}$  but peaked at a depth of  $0.9 R_{\odot}$ , and its amplitude correlated with the sunspot number (Chou and Dai, 2001; Chou and Ladenkov, 2005). This phenomenon was confirmed by other authors (Beck et al., 2002) and by our recent results (Serebryanskiy et al., 2011). Our recent study using GONG++ and SOHO/MDI data shows the meridional flow speed increasing with depth, although the absolute flow speed may have suffered from systematic effects. This research was carried out as a close collaboration between the UBAI, the Astrophysical Laboratory of the NTHU, the National Solar Observatory (NSO) at Tucson, Arizona) and New Mexico State University (NMSU) at Las Cruces, New Mexico, USA).

#### 4.2.3 Searching for Magnetic Fields near the Base of the Solar Convection Zone

It is generally believed that solar magnetic fields are generated near the base of the convection zone. The detection of variations in the physical

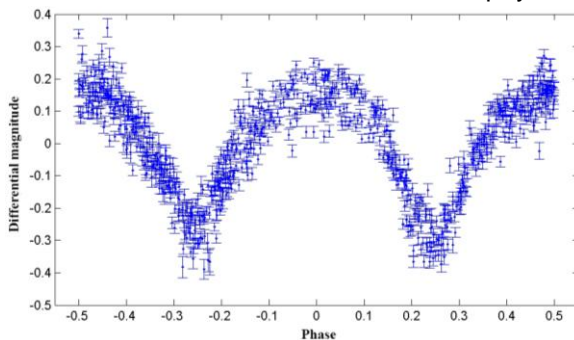


Figure 13: A light curve of the variable star GSC 02007-00761, which was found to be a close binary system rather than a  $\delta$  Scuti variable (after: Ehgamberdiev et al., 2008: 358).

parameters of the solar-cycle near the base of the convection zone could indicate the existence of magnetic fields there. The time-distance technique can be used to measure solar-cycle variations in the travel time around the Sun of particular wave packets formed by p-modes to indicate the presence of magnetic fields near the base of the convection zone (Chou and Serebryanskiy, 2002; Chou et al., 2003). Another means of probing the solar interior is to use the solar-cycle variations of p-mode frequencies, normalized by mode mass, as a function of phase speed. Using this method, the TON team was able to infer magnetic field strengths of between  $1.7 \times 10^5$  G and  $2.9 \times 10^5$  G near the base of the convection zone (Chou and Serebryanskiy, 2005; Serebryanskiy and Chou, 2005). These results were cited as among the most interesting results in astrophysics in 2005 and 2006 (see Trimble et al., 2006; Trimble et al., 2007). Recently, this result also was confirmed by Baldner and Basu (2009).

## 5 ASTEROSEISMOLOGY

Having both a rich heritage in variable star research (Grankin, 1999; Grankin et al., 2007; Mel'nikov and Grankin, 2005; Shevchenko et al., 1993) and solid experience in helioseismology, it was natural that the UBAI team should turn its vision towards asteroseismology, which represents the most efficient method to study stellar interiors in detail. Asteroseismology also uses the observed pulsation spectrum to determine the current structural properties of a given star, from which we may deduce its evolutionary history. Indeed, the theory of stellar evolution need no longer depend solely on theory and measurements made on one unique star, our Sun, now that several classes of known pulsating stars can be studied using this seismic technique.

Currently,  $\delta$  Scuti stars are among the most promising candidates for asteroseismological analysis. These stars are more massive or more evolved than the Sun. Their structure is drastically different, with only a thin convective layer near the surface and two different regions deep inside where nuclear hydrogen-burning occurs. They also exhibit a wide variety of pulsation behavior, with enough amplitude to be detected by ground-based observations. They can then provide relatively easy access to seismic parameters, and nicely complement solar studies. An important feature of these stars for us is their relatively bright magnitude and high amplitude variability. The consequence is that they do not necessarily require a space mission, and we can use several small-aperture telescopes located at different longitudes, just as we did with the IRIS network.

In 2006 we began to establish a network of six educational observatories located at Uzbekistan universities. All were equipped with small telescopes. We found that the observation of  $\delta$  Scuti stars also was an ideal means for teaching students some of the basics of scientific research, and it also was a good way of obtaining real scientific data at a relatively low cost.

Figure 13 shows a result of this observing campaign. Using the 20-inch Grubb-Parsons telescope installed at the Educational Observatory of the Samarkand State University, in 2006 we and students from the University were able to obtain a light curve of the variable star GSC 02007-00761, which was thought to be a  $\delta$  Scuti star. However, the analysis of this light curve allowed us to confirm that this star was not a  $\delta$  Scuti variable, but in fact was a close binary system. We determined the main parameters of this double system and precisely measured its period: 0.2709 days. We also obtained the temperature, radius and mass of each component of this system. More details can be found in Ehgamberdiev et al. (2008).

In order to carry out long-term international observations of  $\delta$  Scuti stars and perform asteroseismic analyses of their light-curves Taiwanese astronomers established the TAT (Taiwan Automated Telescope) network (Chou et al., 2006). In 2007 a TAT was installed at Maidanak Observatory in Uzbekistan, and this is shown in Figure 14. Maidanak Observatory is located in the southern part of Uzbekistan, at an altitude of 2,700 m above mean sea level (Ehgamberdiev et al., 2000).

The TAT network has proved to be quite efficient in finding new  $\delta$  Scuti stars. In 2008 HD 163032 was discovered to be a  $\delta$  Scuti star, and after four years of observations we were able to precisely determine the mode parameters and their variation with time (Fernández, et al., 2013). We also determined these same parameters for another already-known  $\delta$  Scuti star, V830 Her (ibid.; see Figure 15).

Later we turned our TAT towards one of the targets of the Kepler space mission: NGC6811. Our main program was to conduct light-curve analyses of known variable stars, and to make follow-up observations for Kepler. At the time we wrote this paper we had obtained light curves of stars in the field of NGC6811 and discovered several new  $\delta$  Scuti candidates, but were awaiting the arrival of Kepler observations.

## 6 CONCLUDING REMARKS

IRIS was a network for full-disc helioseismology, with six observing stations distributed around the Earth. This project was initiated by Eric Fossat and Gerard Grec from the University of Nice after almost fifteen years experience in researching solar oscillations. They realised that a spectrophotometer which detected Doppler shifts of the sodium D1 line integrated over the whole visible disk of the Sun would allow astronomers to investigate the deep interior of the Sun.

The IRIS network has provided astronomers with the longest time series of full-disc helioseismological data. Freely available on the CDS data base, the eleven years of data for 1989–2000 cover a complete solar cycle, from the maximum of Cycle 22 to the maximum of Cycle 23.

The most crucial achievement on the way to the success of the IRIS project was the scientific involvement of local teams, and the commitment of an IRIS community of enthusiastic and qualified astronomers from different countries.

From 1988, the IRIS group organized thirteen annual workshops, in France, Uzbekistan, Morocco, Spain, England, Italy and the U.S.; provided observations for twelve Ph.D. theses; and successfully produced data and results despite a very modest level of financial support (between 1% and 10% of the support enjoyed by the other



Figure 14: The Taiwan Automated Telescope at Maidanak Observatory (photograph: A. Serebryanskiy).

networks). The spirit of real co-operation was a key to this success, and the local teams, often at remote sites, were fully included in the scientific exploitation of the data bank. Five specific ‘cooperant’ (alternative military service) positions were awarded to the IRIS program, four in Uzbekistan and one in Australia, and University of Nice post-doctoral fellowships were awarded to many of our colleagues.

Many former Uzbek members of the IRIS and TON projects are still working in various fields of astronomy. For example, Shukur Kholikov is an Associate Scientist of the GONG helioseismology project (at the National Solar Observatory in Tucson, Arizona); Olga Burtseva is an Assistant Scientist working for the National Solar Observatory’s Integrated Synoptic Program; Alexander Serebryanskiy is now the Head of the Variable Stars and Asteroseismology Department at the UBAI; and Sabit Ilyasov, who has passed his second dissertation (Doctor Nauk) is now a Vice-director of the UBAI.

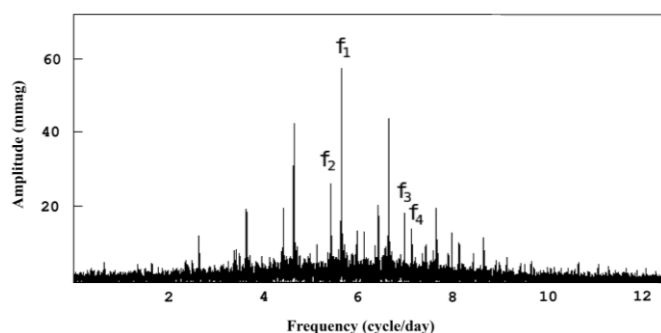


Figure 15: An example of the amplitude spectrum of the  $\delta$  Scuti star V830 Her based on data obtained by the TAT network during 2008-2011 (after Fernández et al., 2013: 36).

## 7 NOTES

1. The TAT uses a 9-cm Maksutov-type telescope with  $f = 25$ , manufactured by Questar. The CCD camera is Apogee Alta U6 16-bit  $1024 \times 1024$ , and the CCD chip is a Kodak KAF-1101E, with a scale of 2.18 arcsecs per pixel, which gives a field of view of  $0.62 \times 0.62$  square degrees.
2. The IRIS scientific committee prepared a text of the Acknowledgments that should accompany each paper written using IRIS data. However, this text was prepared at the beginning of the IRIS project and was never upgraded. As a result, a number of colleagues who joined the community later and made crucial contributions to the success of the project are not mentioned in these Acknowledgments. So, we present an updated version of the Acknowledgments below.

## 8 ACKNOWLEDGMENTS<sup>2</sup>

Data from the IRIS network depended on the coordinated efforts of many people from several nations. The authors wish to thank those who conceived the instrument: E. Fossat and G. Grec; those who contributed to build and maintain all instruments on site: B. Gelly, J.F. Manigault, G. Rouget, J. Demarcq, G. Galou, A. Escobar, J.M. Robillot; those who operated the observing sites: M. Baijumamov, S. Ehgamberdiev, S. Ilyasov, S. Khalikov, I. Khamitov, G. Menshikov, S. Raubaev, T. Hoeksema, Z. Benkhaldoun, M. Lazrek, S. Kadiri, H. Touma, M. Anguera, A. Jimenez, P.L. Palle, A. Pimienta, C. Regulo, T. Roca Cortes, L. Sanchez, F.X. Schmider; R. Luckhurst; those who developed the analysis software: S. Ehgamberdiev, S. Khalikov, E. Fossat, B. Gelly, M. Lazrek, P.L. Palle, L. Sanchez, E. Gavryuseva, V. Gavryusev; and those who contributed to the success of the IRIS project in other critical ways: P. Delache, D. Gough, I. Roxburgh, F. Hill, T. Roca Cortes, G. Zatspepin, T. Yuldashbaev, L. Woltjer, G. Van der Laan, D. Hofstadt, J. Kennewell, D. Cole, P.H. Scherrer, F. Sanchez and J.P. Veziant.

The IRIS group is grateful to A. Cacciani, BiSON, IAC and HAO teams for sharing the Magneto-Optical Filter, Mark-1 and LOWL data, and acknowledges the LOWL observers Eric Yasukawa and Darryl Koon.

Our special thanks go to D. Fierry-Fraillon, S. Loudagh, A. Pantel, D. Salabert, A. Serebryanskiy and S. Tomczyk, who joined the IRIS community later, for their important contributions to the IRIS data analyses at the later stages of the project.

As for the participation of the UBAI team in the TON and TAT projects, this would not have been possible without the very friendly attitude and support of Professor Dean-Yi Chou, with

whom the UBAI has had a very fruitful collaboration in helioseismology since the mid-1990s. He also provided his personal support to UBAI team members who visited the NHTU as post-docs and visiting scientists. The UBAI would also like to express its gratitude to Dean-Yi Chou for his continuous support in various ways of the asteroseismology research carried out with the TAT at Maidanak Observatory.

## 9 REFERENCES

- Athay, R.G., 1970. A non-LTE line-blanketed solar model. *Astrophysical Journal*, 161, 713-735.
- Baijumanov, A., Ehgamberdiev, S., Fossat, E., Grec, G., Ilyasov, S., Kamaldinov, A., Khalikov, S., Khamitov, I., Manigault, J.F., Menshikov, G., Raubaev, S., and Yuldashbaev, T., 1991a. Global oscillation measurements at Kumbel station in frame of the IRIS program. In Ehgamberdiev and Fossat, 51-56.
- Baijumanov, A., Ehgamberdiev, S., Fossat, E., Gelly, B., Ilyasov, S., Khalikov, Sh., Khamitov, I., Menshikov, G., Raubaev, S., and Yuldashbaev, T., 1991b. The Kumbel IRIS site report. In *Proceedings of the IIIrd IRIS Workshop, Marrakech, 1-5 Oct. 1990*. Marrakech, National Centre for Coordination and Planning of Scientific and Technical Research. Pp. 41-42.
- Baldner, C.S., and Basu, S., 2009. Solar cycle related changes at the base of the convection zone. *Astrophysical Journal*, 686, 1349-1361.
- Beck, J.G., Gizon, L., and Duvall T.L., 2002. A new component of solar dynamics: north-south diverging flows migrating toward the equator with an 11 year period. *Astrophysical Journal*, 575, L47-L50.
- Buckingham, M.J., Berknot, B.V., and Glegg, S.A.L., 1992. Imaging the ocean with ambient noise. *Nature*, 356, 327-329.
- Burtseva, O., Kholikov, S., Serebryanskiy, A., and Chou, D.-Y., 2007. Effects of dispersion of wave packets in the determination of lifetimes of high-degree solar p modes from time distance analysis: TON data. *Solar Physics*, 241, 17-25.
- Burtseva, O., Hill, F., Kholikov, S., and Chou D.-Y., 2009. Lifetimes of high-degree p modes in the quiet and active Sun. *Solar Physics*, 258, 1-11.
- Cacciani, A., and Fofi, M., 1978. The magneto-optical filter. II. Velocity field measurements. *Solar Physics*, 59, 179-189.
- Cacciani, A., Rosati, P., Ricci, D., Marquedant, R., and Smith, E., 1988. Integrated solar disk oscillation measurements using the magneto-optical filter: tests with a two station network. In Rolf, E.J. (ed.). *Seismology of the Sun and Sun-like Stars*. Paris, European Space Agency. Pp. 181-184.
- Chang, H.-K., Chou, D.-Y., Labonte B., and the TON Team, 1997. Ambient acoustic imaging in helioseismology. *Nature*, 389, 825.
- Chaplin, W.J., Elsworth, Y., Isaak, G.R., Miller, B.A., and New, R., 1999. Skew-symmetric solar p-modes in low-l BiSON data. *Monthly Notices of the Royal Astronomical Society*, 308, 424-430.
- Chen, H.-R., Chou, D.-Y., Chang, H.-K., Sun, M.-T., Yeh, S.-J., LaBonte, B., and the TON Team, 1998. Probing the subsurface structure of active regions with the phase information in acoustic imaging. *Astrophysical Journal Letters*, 501, L139-L144.

- Chou, D.-Y., Sun, M.-T., Huang, T.-Y., Jimenez, A., Lai, S.-P., Chi, P.-J., Ou, K.-T., Wang, C.-C., Lu, J.-Y., Chu, A.-L., Niu, C.-S., Mu, T.-M., Chen, K.-R., Chou, Y.-P., Chao, H., Rabello-Soares, M.C., Ai, G., Wang, G.-P., Zirin, H., Marquette, W., and Nenow, J., 1995. Taiwan Oscillation Network. *Solar Physics*, 160, 237-243.
- Chou, D.-Y., Chang, H.-K., Sun, M.-T., LaBonte, B., Chen, H.-R., Yeh S.-J., and the TON Team, 1999. Acoustic imaging in helioseismology. *Astrophysical Journal*, 514, 979-988.
- Chou, D.-Y., 2000. Acoustic imaging of solar active regions. *Solar Physics*, 192, 241-259.
- Chou, D.-Y., and Dai, D.-C., 2001. Solar cycle variations of subsurface meridional flows in the Sun. *Astrophysical Journal*, 559, L175-L178.
- Chou, D.-Y., Serebryanskiy, A., Ye, Y.-J., Dai, D.-C., and Khalikov, S., 2001. Lifetimes of high- $l$  solar p-modes from time-distance analysis. *Astrophysical Journal*, 554, L229-L231.
- Chou, D.-Y., and Serebryanskiy, A., 2002. Searching for the signature of the magnetic fields at the base of the solar convection zone with solar cycle variations of p-mode travel time. *Astrophysical Journal*, 578, L157-L160.
- Chou, D.-Y., Serebryanskiy, A., and Sun M.-T., 2003. Probing solar subsurface magnetic fields. *Space Science Reviews*, 107, 35-42.
- Chou, D.-Y., and Serebryanskiy, A., 2005. In search of the solar cycle variations of p-mode frequencies generated by perturbations in the solar interior. *Astrophysical Journal*, 624, 420-427.
- Chou, D.-Y., and Ladenkov, O., 2005. Evolution of solar subsurface meridional flows in the declining phase of cycle 23. *Astrophysical Journal*, 630, 1206-1212.
- Chou, D.-Y., Sun, M.-T., and Yang, M.-H., 2006. Earthshine and Asteroseismology Telescope (East) Network. *Space Science Reviews*, 122, 221-228.
- Chou, D.-Y., and Ladenkov, O., 2007. Effects of dispersion of wave packets in the determination of lifetimes of high-degree solar p modes from time distance analysis: MDI data. *Solar Physics*, 241, 7-15.
- Deubner, F.-L., 1975. Observations of low-wavenumber nonradial eigenmodes of the Sun. *Astronomy & Astrophysics*, 44, 371-375.
- Di Mauro, M.P., Dziembowski, W.A., and Paternó, L., 1998. Rotation of the solar interior: new results by helioseismic data inversions, structure and dynamics of the interior of the Sun and Sun-like stars. In SOHO 6/GONG 98 Workshop Abstract, June 1-4, Boston, Massachusetts, p. 759.
- Ehgamberdiev, S., and Fossat, E. (eds.), 1991. *Proceedings of the 2<sup>nd</sup> IRIS Workshop, held at Tashkent, Uzbekistan, September 1989*. Special Issue of *Solar Physics*, 133
- Ehgamberdiev, S.A., and Khamitov, I.M., 1991. On the calculation of spurious velocity signal produced by atmospheric differential extinction in whole disk velocity measurements. In Ehgamberdiev and Fossat, 81-88.
- Ehgamberdiev, S., Khalikov, S., and Fossat, E., 1991a. General presentation of a single IRIS site raw data analysis problem. In Ehgamberdiev Fossat, 69-80.
- Ehgamberdiev, S., Fossat, E., Gelly, B., Khalikov, S., Lazrek M., Palle, P.L., and Sanchez, L., 1991b. Raw data software team report. In *Proceedings of the 3<sup>rd</sup> IRIS Workshop, Marrakech, 1-5 Oct.1990*. Marrakech, National Centre for Coordination and Planning of Scientific and Technical Research. Pp. 18-21.
- Ehgamberdiev, S., Khalikov, S., Lazrek, M., and Fossat, E., 1992. Amplitude modulation of low-degree solar p-modes. *Astronomy & Astrophysics*, 253, 252-260.
- Ehgamberdiev, S., Fossat, E., Khamitov, I., and Kulshova, K., 1993. Is the power above the cut-off frequency correlated with the solar activity? In Cortes, T.R., and Garcia, N. (eds.). *Proceedings of the V-th IRIS Workshop & GOLF'93 Annual Meeting. Tacoronte, Tenerife (Spain)*. IAC. Pp. 35-38.
- Ehgamberdiev, S., Khalikov, S., Fossat, E. et al., 1997. Variation of the cut-off frequency with solar cycle. In Cacciani, A. (ed.). *IXth IRIS Workshop, Capodimonte, Italy, 30 June-5 July 1997*. Sapienza, Università di Roma. Pp. 18-23.
- Ehgamberdiev, S.A., Baijumanov, A., Ilyasov, S.P., Sarazin, M., Tillaev, Y.A., Tokovinin, A.A., and Ziad, A., 2000. The astroclimate of the Maidanak Observatory in Uzbekistan. *Astronomy & Astrophysics, Supplement Series*, 145, 293-304.
- Ehgamberdiev, S.A.; Serebryanskiy, A.V., Khalikov, S.S., Fossat, E., Gelly, B., and the IRIS Team, 2001. An estimation of global p-mode frequencies and splitting from the IRIS Network data: 1989-1996. In Brekke, P., Fleck, B., and Gurman, J.B. (eds.). *Recent Insights into the Physics of the Sun and Heliosphere: Highlights from SOHO and Other Space Missions*. San Francisco, Astronomical Society of the Pacific, 97-100.
- Ehgamberdiev, S.A., Serebryanskiy, A.V., Khalikova, D.A., Sharapov, D., Tillaev, Y., Ajabov, A., Juraev, B., and Zakhidov, A.S., 2008. Light curve analysis of GSC 02007-00761: first observations at Samarkand astronomical observatory. *Uzbek Physics Journal*, 10, 357-363 (in Russian).
- Ehgamberdiev, S., and Serebryanskiy, A., 2011. Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences - history and current status of solar physics research. First Asia-Pacific Solar Physics Meeting, ASI Conference Series. *Bulletin of the Astronomical Society of India*, 2, 405-409.
- Einstein, A., 1915. Erklärung der Perihelbewegung des Merkur aus der allgemeinen Relativitätstheorie. *Preussische Akademie der Wissenschaften, Sitzungsberichte*, 2, 831-839.
- Elsworth, Y.P., Isaak, G.R., Jefferies, S.M., McLeod, C.P., New, R., van der Raay, H.B., Palle, P., Regulo, C., Roca, C.T., 1988. Experience in operating a limited global network of stations measuring full-disk oscillations of the Sun. In Christensen-Dalsgaard, J., and Frandsen, S. (eds.). *Advances in Helio- and Asteroseismology*. Dordrecht, Reidel. Pp. 535-539.
- Elsworth, Y., Howe, R., Isaak, G.R., McLeod, C.P., Miller, B.A., Wheeler, S.J., and Dough D.O., 1995. Slow rotation of the Sun's interior. *Nature*, 376, 669-672.
- Fernández, J., Chou, D.-Y., Wang, L.-H., Sun, M.-T., Jiménez, A., Serebryanskiy, A., Strel'nikov, D., and Ehgamberdiev, S., 2013. Mode parameters of  $\delta$  Scuti stars V830 Her and HD 163032 with four-year data from the Taiwan Automated Telescope Network. *Publications of the Astronomical Society of the Pacific*, 125, 31-40.
- Fossat, E., 1991. The IRIS for full disk helioseismol-

- ogy: present status of the programme. In Ehgamberdiev and Fossat, 1-12.
- Fossat, E., 1992. IRIS data merging. I. A solution to minimize the low and intermediate frequency noise. *Astronomy & Astrophysics*, 263, 443-452.
- Fossat, E., Regulo, C., Roca, C.T., Ehgamberdiev, S., Gelly, B., Grec, G., Khalikov, S., Khamitov, I., Lazrek, M., Palle, P.L., and Sanchez, D.L., 1992. On the acoustic cut-off frequency of the Sun. *Astronomy & Astrophysics*, 266, 532-536.
- Fossat, E., Lazrek, M., Loudach S., Pantel, A., Gelly, B., Grec, G., Schmider, F.X., Palle, P., Regulo, C., Ehgamberdiev, S., Khalikov, S., and Hoeksema, J.T., 1995. Solar core rotation: latest IRIS results. In Hoeksema, J.T., Domingo, V., Fleck, B., and Battrick, B. (eds). *Proceedings of the 4<sup>th</sup> SOHO Workshop: Helioseismology, Asilomar Conference Center, Pacific Grove, California, USA, 2-6 April*. Paris, European Space Agency. Pp. 64-66.
- Fossat E., Kholikov, S., Gelly, B., Schmider, F.X., Fierry-Fraillon, D., Grec, G., Palle, P., Cacciani, A., Ehgamberdiev, S., Hoeksema, J.T., and Lazrek, M., 1999. Full disk helioseismology: repetitive music and the question of gap filling. *Astronomy & Astrophysics*, 343, 608-614.
- Fossat, E., and the IRIS team, 2002. 11 years of IRIS network exploitation. In Combes, F., and Barret, D. (eds.). *SF2A-2002: Semaine de l'Astrophysique Francaise*. Paris, EdP-Sciences. P. 521.
- Fossat, E., 2013. Early South Pole observations and the IRIS Network: the quarter century history of a small sodium cell. In Jain, K., Tripathy, C.S., Hill, F., Leibacher, J.W., and Pevtsov, A.A. (eds.). *Fifty Years of Seismology of the Sun and Stars. Proceedings of a Workshop held 6-10 May, 2013 in Tuscon, Arizona, USA*. San Francisco, Astronomical Society of the Pacific. Pp.73-84.
- Gabriel, M., and Lazrek, M., 1994. On the amplitude modulation of acoustic modes. *Astronomy & Astrophysics*, 286, 635-638.
- Gelly, B., Fierry-Fraillon, D., Fossat, E., Palle, P., Cacciani, A., Ehgamberdiev, S., Grec, G., Hoeksema, J.T., Khalikov, S., Lazrek, M., Loudagh, S., Pantel, A., Regulo, C., and Schmider, F.X., 1997. Solar P-mode frequencies from the IRIS network. *Astronomy & Astrophysics*, 323, 235-242.
- Gelly, B., Lazrek, G., Grec, A.A., Schmider, F.X., Renaud, C., Salabert, D., and Fossat, E., 2002. Solar p-modes from 1979 days of the GOLF experiment. *Astronomy & Astrophysics*, 394, 285-297.
- Gizon, L., Fossat, E., Lazrek, M., Cacciani, A., Ehgamberdiev, S., Gelly, B., Grec, G., Hoeksema, J.T., Khalikov, S., Palle, P.L., Pantel, A., Regulo, C., Schmider, F.X., and Wilson, P.R., 1997. New IRIS constraints on the solar core rotation. *Astronomy & Astrophysics*, 317, L71-L74.
- Grankin, K.N., 1999. Evolution of the light curve of V410 Tau during 1986-1997. *Astronomy Letters*, 25, 526-535.
- Grankin, K.N., Melnikov, S.Yu., Bouvier, J., Herbst, W., and Shevchenko, V.S., 2007. Results of the ROTOR-program. I. The long-term photometric variability of classical T Tauri stars. *Astronomy & Astrophysics*, 461, 183-195.
- Grec, G., Fossat, E., and Pomerantz M.A., 1980. Solar oscillations: full disk observations from the Geographical South Pole. *Nature*, 288, 541-544.
- Grec, G., Fossat, E., and Pomerantz M.A., 1983. Full disk observations of solar oscillations from the Geographical South Pole: latest results. *Solar Physics*, 82, 55-66.
- Grec, G., Fossat, E., Gelly, B., and Schmider F.X., 1991. The IRIS Sodium Cell Instrument. In Ehgamberdiev and Fossat, 13-30.
- Harvey, J., 1985. High-resolution helioseismology. In Rolfe, E., and Patrick, B., (eds.). *Future Missions in Solar, Heliospheric and Space Plasma Physics*. Noordwijk, European Space Agency. Pp.199-208.
- Harvey, J.W., Hill, F., Hubbard, R.P., Kennedy, J.R., Leibacher, J.W., Pintar, J.A., Gilman, P.A., Noyes, R.W., Tittle, A.M., Toomre, J., Ulrich, R.K., Bhatnagar, A., Kennewell, J.A., Marquette, W., Patron, J., Saa, O., and Yasukawa, E., 1996. The Global Oscillation Network Group (GONG) Project. *Science*, 272, 1284-1286.
- Houdek, G., Chaplin, W.J., Appourchaux, T., Christensen-Dalsgaard, J., Däppen, W., Elsworth, Y., Gough, D.O., Isaak, G.R., New, R., and Rabello-Soares, M.C., 2001. Changes in convective properties over the solar cycle: effect on p-mode damping rates. *Monthly Notices of the Royal Astronomical Society*, 327, 483-487.
- Ilyasov, S., Baijumanov, A., Ehgamberdiev, S., Fossat, E., Grec, G., Khalikov, S., Khamitov, I., Menshikov, G., Raubaev, S., and Yuldashbaev, T., 1993. Kumbel site report, 1992. In Cortes, T.R., and Garcia, N. (eds.). *Proceedings of the V-th IRIS Workshop & GOLF'93 Annual Meeting, Tacoronte, Tenerife (Spain)*. IAC. Pp. 1-3.
- Kholikov, S.S., Burtseva, O.S., Serebryanskiy, A.V., and Ehgamberdiev, S.A., 2004. On the variations in the parameters of high-degree acoustic modes with solar cycle. *Astronomy Letters*, 30, 577-581.
- Lazrek, M., Pantel, A., Fossat E., Gelly, B., Schmider, F.X., Fierry-Fraillon, D., Grec, G., Loudach, S., Ehgamberdiev, S., Khamitov, I., Hoeksema, J.T., Palle, P., and Regulo, C., 1996. Is the solar core rotating faster or slower than the envelope? *Solar Physics*, 166, p.1-16.
- Leibacher, J.W., and Stein, R.F., 1971. A new description of the solar five-minute oscillation. *Astrophysical Letters*, 7, 191-192.
- Leighton, R.B., Noyes, R.W., and Simon, G.W., 1962. Velocity fields in the solar atmosphere. I. Preliminary report. *Astrophysical Journal*, 135, 474-499.
- Libbrecht, K.G., 1988. Solar and stellar seismology. *Space Science Reviews*, 47, 275-301.
- Lindsey, C., and Braun, D.C., 1997. Acoustic holography. *Astrophysical Journal*, 485, 895-903.
- Loudagh, S., Provost, J., Berthomieu, G., Ehgamberdiev, S., Fossat, E., Gelly, B., Grec, G., Khalikov, S., Lazrek, M., Palle, P., Sanchez, L., and Schmider, F.X., 1993. A measurements of the  $l = 1$  solar rotational splitting. *Astronomy & Astrophysics*, 275, L25-L28.
- Melnikov, S.Yu., and Grankin, K.N., 2005. Study of the optical variability of T Tau in the period 1962-2003. *Astronomy Letters*, 31, 109-116.
- Muller, R., 1988. Variability of solar granulation. *Advances in Space Research*, 8, 159-167.
- Nigam, R., and Kosovichev, A.G., 1998. Measuring the Sun's eigenfrequencies from velocity and intensity helioseismic spectra: asymmetrical line profile-fitting formula. *Astrophysical Journal Letters*, 505, L51-L54.



- Paternò, L., Di Mauro, M.P., and R. Ventura, 2003. From helio- to astero-seismology, a new challenge for understanding stellar evolution. In Pandarai, S.C. (ed.). *Recent Research Developments in Astronomy & Astrophysics. Volume 1, Part 1*. Trivandrum, Research Signpost Publications. Pp. 523-560.
- Salabert, D., Jimenez-Reyes, S.J., Fossat, E., Cacciani, A., Ehgamberdiev, S., Gelly, B., Grec, G., Hoeksema, J.T., Khalikov, S., Lazrek, M., and 3 co-authors, 2002. Analysis of variability of p-mode parameters in 11 years of IRIS data. In Sawaya-Lacoste, H. (ed.). *Proceedings of the Second Solar Cycle and Space Weather Euroconference, 24 - 29 September 2001, Vico Equense, Italy*. Noordwijk, European Space Agency. Pp. 253-256.
- Salabert, D., Fossat, E., Gelly, B., Tomczyk, S., Palle, P., Jimenez-Reyes, S.J., Cacciani, A., Corbard, T., Ehgamberdiev, S., Grec, G., and 4 coauthors, 2002. IRIS<sup>++</sup> database: merging of IRIS + Mark-1 + LOWL. *Astronomy & Astrophysics*, 390, 717-723.
- Salabert, D., Fossat, E., Gelly, B., Kholikov, S., Grec, G., Lazrek, M., and Schmider, F.X., 2004. Solar p-modes in 10 years of the IRIS network. *Astronomy & Astrophysics*, 413, 1135-1142.
- Scherrer, P.H., Bogart, R.S., Bush, R.I., et al., 1995. The solar oscillations investigation - Michelson doppler imager. *Solar Physics*, 162, 129-188.
- Serebryanskiy, A., Ehgamberdiev, S., Khalikov, S., Fossat, E., Lazrek, M., Gelly, B., Schmider, F.X., Fierry Fraillon, D., Grec, G., Palle, P., Cacciani, A., and Hoeksema, J.T., 1998. Solar cycle dependence of the acoustic cut-off frequency for low-l modes. In Ehgamberdiev, S. (ed.). *Proceedings of the Xth IRIS/TON Workshop, Parkent (Uzbekistan)*. Tashkent, Ulugh Beg Astronomical Institute. Pp.17-19.
- Serebryanskiy, A., Ehgamberdiev, S., Kholikov, S., Fossat E., Gelly, B., Schmider, F.X., Grec, G., Cacciani, A., Palle, P., Lazrek, M., and Hoeksema, J.T., 2001. An estimation of global solar p-mode frequencies from IRIS network data: 1989-1996. *New Astronomy*, 6, 189-195.
- Serebryanskiy, A., and Chou, D.-Y., 2005. Comparison of solar cycle variations of solar p-mode frequencies from GONG and MDI. *Astrophysical Journal*, 633, 1187-1190.
- Serebryanskiy, A., Kholikov, S., Hill, F., and Jackie-wicz J., 2011. Meridional circulation measurements from 15 years of GONG. American Astronomical Society, SPD meeting #42, #16.14. *Bulletin of the American Astronomical Society*, 43.
- Serebryanskiy, A.V., Gaynullina, E.R., Strel'nikov, D.V., and Khalikova, A.V., 2013. Variability type of BD+ 46 d2731. *Information Bulletin on Variable Stars*, 6047, 1-6.
- Shevchenko, V.S., Grankin, K.N., Ibragimov, M.A., Melnikov, S.Y., and Yakubov, S.D., 1993. Periodic phenomena in Ae/Be Herbig Star lightcurves. II: Results and probable interpretation for selected stars. *Astrophysics and Space Science*, 202, 137-154
- Tomczyk, S., Strender, K., Card, G., Elmore, D., Hull, H., and Cacciani, A., 1995. An instrument to observe low-degree solar oscillations. *Solar Physics*, 159, 1-21.
- Trimble, V., Aschwanden, M.J., and Hansen, C.J., 2006. Astrophysics in 2005. *Publications of the Astronomical Society of the Pacific*, 118, 947-1047.

Trimble, V., Aschwanden, M.J., and Hansen, C.J., 2007. Astrophysics in 2006. *Space Science Review*, 132, 1-182.

Ulrich, R.K., 1970. The five-minute oscillation on the solar surface. *Astrophysical Journal*, 162, 993-1002.

Dr Shuhrat Ehgamberdiev is the Director of the Ulugh Beg Astronomical Institute in Tashkent. His scientific interests include helio- and asteroseismology, astro-climate and history of astronomy. He has organized several workshops and conferences. He also devotes a lot of his time to popularizing science in Uzbekistan, and since 2002 has edited the *Fan va Turmush (Science and Life)* magazine. Under his supervision the deployment of a network of educational astronomical observatories around Uzbekistan was initiated. He is a member of the IAU and the Eurasia Astronomical Union, and during 2002-2003 was the General Secretary of the Asian Academies of Science Association. He is the author or coauthor of more than 120 scientific papers and is the author of 80 newspaper articles. He has supervised 10 Ph.D. students, and currently lectures at the Uzbekistan National University and at Samarkand State University.



Dr Eric Fossat is an Emeritus astronomer at the Observatoire de la Cote d'Azur in Nice, France, and shares his time between the Observatory and University of Nice. His scientific career has mainly focused in two directions: Firstly, he was among the early pioneers in helioseismology, with the first identification of individual solar frequencies made possible by the first ever expedition of optical astronomers at the geographic South Pole, and then as the author and the P.I. of the IRIS world-wide network. Secondly, for ten years he was the P.I. of the Astronomical French Research programme in Antarctica, at the Concordia station located at Dome C on the polar plateau. He has published more than 200 scientific papers, supervised 15 Ph.D. theses, and received many awards: from the USA (the Antarctic Medal of the National Science Foundation), Belgium (the Gold Medal of the Royal Academy of Science), and France (CNRS Medal, Prix 'Petit d'Ormy' from Academy of Science, and the 'Prix du Rayonnement Français' for his international activities).



Alexander Serebryanskiy is the Head of the Variable Stars and Asteroseismology Department at the Ulugh Beg Astronomical Institute in Tashkent. He started his scientific career at UBAI in 1994 as an

observer at the Kumbel station of the IRIS project. Later, in 1996, he joined the TON project as an observer and data reduction scientist. In 2000 he defended his Ph.D. thesis, which was devoted to a study of the Sun using global helioseismology observations obtained through the IRIS network. Since 2000 his scientific interest has also included local helioseismology. He



was a postdoc at the National Tsing Hua University in Tai-wan where he worked with Dean-Yi Chou studying the solar interior using TON and SOHO/MDI data. He was a postdoc in 2004-2005 at the National Solar Observatory in the USA where he worked with the GONG team and studied the solar interior using GONG and SOHO/MDI data. Since 2001 he has been the author or coauthor of more than 25 publications.

## APPENDIX 1: A HISTORY OF KUMBEL STATION OF THE IRIS NETWORK

by Shuhrat Ehgamberdiev

Within the distribution of the northern hemisphere sites selected for the worldwide IRIS network, one instrument had to be installed somewhere in Central Asia. In the 1980s this area was referred to as the south of the Soviet Union. Immediately after receiving funding from INSU—the French Institute for the Studies of the Universe—in 1984, Eric Fossat and Gerard Grec from the University of Nice headed to the unknown, for them, “... country of the Soviets ...”, aiming to find a site where they could install an IRIS instrument.

They arrived at ASTROSOVET (the Astronomical Council), an organization based in Moscow that coordinated academic research in the field of astronomy for the whole of the USSR. Staff at ASTROSOVET strongly advised Fossat and Grec to go to the Crimean Astrophysical Observatory, which at that time was the center of Soviet helioseismology. In fact, its Director, the well-known astrophysicist, Academician Andrei Severny, a few years earlier had announced the sensational discovery of the 160-minute oscillation of the Sun, which he interpreted as reflecting a gravitational mode of the Sun. However, these 160-minute oscillations have not been substantiated either by the IRIS data or by any other contemporary solar observations, and the historical signal is now considered to occur during the redistribution of power from the diurnal cycle as a result of the observation window and atmospheric extinction. Today little attention is paid to this topic, but in the 1980s it was widely discussed at all conferences on helioseismology

Meanwhile, the identification of gravity modes remains one of the key challenges of helioseismology.

It was no surprise that it was left to Severny to decide on where in the USSR the French telescope should be installed, and he proposed to have it in the Crimea. However, the astroclimate of Crimea did not differ markedly from that of Nice, which did not suit the French astronomers. The high humidity and frequent clouds along the sunny shores of the Crimean Peninsula made it quite unsuitable for whole-disc observations of solar oscillations, which are highly sensitive to the transparency of the atmosphere.

The next time Eric Fossat and his colleague Jean-Francois Manigault arrived in the USSR they contacted another famous Soviet scientist, Academician George Zatsepin, who ran the Bak-san Neutrino Observatory of the Institute of Nuclear Research (INR) of the Soviet Academy of Sciences, located in the Caucasus. Zatsepin helped organizing a trip to Uzbekistan for the French scientists, accompanied by his collaborator, Elena Gavryuseva, and they arrived in Tashkent in the fall of 1985.

This was when I first met Fossat and Manigault. Fall is a great season in Uzbekistan, not only because this time of year we have the world’s sweetest melons and grapes, but also due to the huge number of clear sunny days. These factors combined to make quite an impression on the French visitors, and soon after an agreement was signed between the University of Nice, the INR and the Astronomical Institute of the Academy of Sciences of Uzbekistan. Although we were real partners with the INR, at that time the Astronomical Institute was not allowed to sign any agreement with a foreign institute by itself, without control from a Moscow institution.

From that time, Uzbek scientists began to be actively involved in helioseismology. The first important decision was to choose a location for the IRIS spectrophotometer. During the visit of the French scientists, the plan was to install the instrument on the premises of the Astronomical Institute in Tashkent, but studies revealed that the dusty skies there during the summer months, when a maximum number of clear days occur, would not allow the acquisition of high-quality data. The solution was to find a site in the mountains where the density of atmospheric dust was much lower, and the natural choice was the mountainous area of Chimghana one hour drive from Tashkent.

As result of many helicopter flights around the Chimgan area, Mt Kumbel, which was located on a spur of the Big Chimgan summit, captured our attention. It was an isolated mountain top

that at the same time provided enough space to accommodate an IRIS station. When we climbed 2,300-m high Mt Kumbel on foot we found that a funicular ski trail had been built there, but the road to the top had not been paved and apparently there were no plans to develop it further. Nevertheless, this serious obstacle did not stop us, as we already were so 'infected' by the idea of having an IRIS station on Mt Kumbel. Pure enthusiasm, multiplied by a lack of experience, proved to be quite a powerful incentive for us. In other words, we were not aware of the enormity of the work and the challenges that we were about to face. In November 1987 Eric Fossat and Gerard Grec visited Mt Kumbel and the seeing impressed them. Our choice was highly approved.

Success in any venture largely depends upon many random circumstances, as well as an element of luck. In order to accommodate our staff of researchers on M. Kimbel we had to buy special caravans, but in a controlled economy it would be almost impossible to make such purchases immediately. These caravans generally were provided, on demand, to construction companies, not to academic institutions, and their requests were made years in advance. Of course the Astronomical Institute could order two of these caravans, but there was a waiting time of many years and our caravans were required urgently.

Oddly, pure chance made it happen for us. I learned from my wife that there was a family of a very influential government official among our neighbors, whose daughter would walk her toddler around the neighborhood along with my wife and our baby daughter. That man was a senior manager of a leading construction company in Uzbekistan. As my wife knew his daughter quite well, the two women arranged for me to meet him. By chance, two construction companies had recently 'terminated' their previous orders, so we could get two caravans to be delivered to our Institute within a couple of weeks.

However, now we had to work out how to transfer one of the caravans to the top of the Mt Kumbel given that there were no roads near the mountain that we could use. Once again, luck was on our side. We had a Civil Defense officer at our Institute, as was required at that time for every state organization. These individuals typically were hired from a pool of military retirees, and their duties included training personnel on how to use personal safety equipment and how to behave in the event of a nuclear attack. Our Civil Defense officer was a former pilot, a wonderful man, and I had a very good working relationship with him. As soon as I informed him of our 'problem', he made a great suggestion. He was residing in a part of Tashkent called

Aviagorodok, which translates as a 'Town of Aviators' because it was built especially for aviation engineers and their families. He knew that the latest Soviet military helicopter was the MI-26, which was used during combat operations in Afghanistan, and he told me that there were a few of these helicopters in Uzbekistan and one of these "... could easily transport your caravan to the top of Mt Kumbel." But the "easily" part turned out to be not so easy at first because all I had to do was get the Chief Commander of the Division that was in charge of the MI-26 to agree to do me a 'small favor'. Through the wife of our Civil Defense officer, who happened to work there, we managed to make contact with the Chief Commander (which was not easy as the Division belonged to the KGB Border Forces). I learned that the Chief Commander was a general, and I wrote him a formal letter requesting his help.

I knew that the Director of our Astronomical Institute at that time would not be willing to sign such a letter, so I drafted the letter on behalf of the President of the Academy of Sciences of Uzbekistan. When I went to get his signature and handed the letter to one of his assistants she looked at me with suspicion and asked: "Does your Director know about this?" to which I replied "yes". But since the addressee of the letter was quite out of the ordinary, she decided to make sure and call my Director. Fortunately, he was not in his office, and since there were no cellphones in those days the fate of this matter was decided.

Armed with the letter signed by the President of the Uzbekistan Academy of Sciences, I went straight to the Chief Commander. Frankly, I was quite overwhelmed by pure excitement: after all, I was a mere junior researcher at a relatively small academic institution, and here I was trying to convince a Soviet Air Force General to take a chance and help me. What if I could not make this happen? That would spell the end of the entire project.

As soon as I arrived at the building where I was supposed to meet the Chief Commander, I informed the Duty Officer that I was there at the request of the President of the Academy of Sciences. Soon another officer appeared who accompanied me to a reception area where I was asked to wait. Finally, I met the Chief Commander, and found myself in a very spacious office. Ironically, I really cannot recall exactly how I started the conversation, but I do remember the most important words that I used, whilst applying my powers of persuasion at that time, were the following, "If we, the scientists, cannot meet the needs of the French scientists and thus disgrace ourselves, then at least, you, the Soviet Army, should show them how powerful

you are.” The Chief Commander burst out laughing, and I knew right then that I had managed to get my point across. He called one of his officers and told him: “Here is a young man who has persuaded us to show our strength to the French. Help him.” Then he added: “We must get his caravan up the mountain.”

We went into a room where many military pilots sat and were discussing details of air battles over Kandahar and Mazar-i-Sharif in Afghanistan. The colonel who was in charge of my case took out a detailed military map and asked me to show him exactly where Mt Kumbel was. Then we agreed that we would go on a ‘reconnaissance mission’ the next day so that he could familiarize himself with precisely where the caravan should be delivered.

When we finally brought the caravan to the designated pick-up point, an MI-26 helicopter was waiting for us. In the course of looking for a place that would be suitable for our IRIS station I had flown frequently on MI-8 helicopters so was quite familiar with them, but when I saw the MI-26 it absolutely astounded me. It picked up our 15-ton caravan as if it was a box of matches and raised it high in the air. While I was in the Chief Commander’s office I overheard pilots discussing details of their upcoming flight, and they warned me that in the event of strong winds and turbulence, for safety reasons they would have to jettison the caravan. But luckily the weather was perfect that day. When the MI-26 helicopter flew to the top of Mt Kumbel a huge cloud of dust appeared so everything underneath was completely invisible. I remember asking the pilots for details about the conditions on the ground, because within a radius of 70 meters from the rotor the MI-26 was similar to a hurricane. They finally landed the caravan, but it was 50 meters away from the intended site. Then the helicopter flew away, and we waved, expressing our deepest gratitude to the pilots and people who helped us make this happen. Subsequently, we utilized methods similar to those used in building the Egyptian pyramids in order to get the caravan precisely to the location we had selected.

Although there is a lot of controversy now about the Soviet era, ordinary people back then were much more honest and decent than these days. Many of the quite difficult matters we faced during the construction process were re-

solved easily, thanks mainly to the support and genuine attitudes of local people. What can one say about the fact that we managed to fly in a military helicopter totally free of charge in order to complete our mission? Or that colleagues from the Hydro-meteorological Center took us along on their flights? Or, finally, that the pilots who were flying us around to so many different places, knowing that we were looking for a site for the observatory, not only made many additional flights, but also would land at some unusual and quite difficult places and then come back to pick us up when we were ready to return home. I can only imagine how much these ‘excursions’ would cost if this were to happen today. And I am not even talking about transferring a caravan to the top of Mt Kumbel.

We all were driven by enormous enthusiasm, and over a period of three months in the summer of 1988 we completed construction of the IRIS station. Although just a handful of staff, we managed to raise and carry several hundred tons of construction materials, each time manually loading and unloading the MI-8 helicopter that we used. We carried out all of the construction ourselves without any assistance from professional construction workers, and our colleagues from France turned out to be not only excellent scientists but also quite skilled construction workers.

Finally, in August 1988 the spectrophotometer was operational and we received our first signal. I remember as if it were yesterday the impact this work made on all of us. Observing the signal registered on a chart-recorder, we were able to see all the components of the radial velocity between the Sun and the telescope. At dawn the IRIS instrument registered the speed at which the Kumbel station and the Earth moved towards the Sun while in the evening the station would move away from the Sun. Day after day, this speed curve shifted as a whole, thus showing how the radial velocity component of the Earth’s orbit changes during our orbit round the Sun. Altogether, all of the components of the radial velocity that should exist were seen through the IRIS instrument, and along this smooth curve one could see tiny ripples. These were the oscillations of the solar surface—the primary objective of our entire adventure.